A geochemical approach to unravelling ice sheet history using both Tellus and Tellus Border soil geochemical data.

Technical Report · October 2013

DOI: 10.13140/RG.2.1.2023.9443

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TELLUS BORDER RESEARCH PROJECT: TECHNICAL REPORT

A geochemical approach to unravelling ice sheet history using both Tellus and Tellus Border soil geochemical data

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EXECUTIVE SUMMARY

This technical report presents the findings of the Tellus Border research project no. 10761: *A geochemical approach to unravelling ice sheet history using both Tellus and Tellus Border soil geochemical data* completed between April and October 2013. The project uses the soil geochemical data compiled by the Tellus Border and Tellus surveys to investigate the provenance of primary glacigenic sediment i.e. till in the north of Ireland with the purpose of identifying the nature of subglacial transport in the study area. This has implications for understanding the genesis of till and subglacial bedforms in the region and contributes to understanding of the history of the Irish Ice Sheet. It is the first regional-scale investigation of geochemistry in the northern sector of the Irish Ice Sheet.

Background

Ice sheets are an integral part of the global climate system and investigating their behaviour provides crucial information on how they respond to and drive climatic changes (McCabe and Clark, 1998). As is the case with most of earth's systems, the key to predicting the future lies in understanding the past and palaeo-ice sheets have left a rich geological record, which can be used to reconstruct former ice sheet events through glacial/deglacial cycles. These palaeo-ice sheet reconstructions provide essential information on the nature and timing of glacial events and the dynamic responses of former ice sheets to climatic forcing over long time scales (e.g. Kleman et al., 1997). This information is essential for helping establish how ice sheets interact with the global climate system and can be used to test the reliability of global climate models and numerical ice sheet models which attempt to model ice sheet responses to future climate change.

The former Irish Ice Sheet is known to have been climatically sensitive to external forcing events in the wider amphi-North Atlantic (McCabe and Clark, 1998) making it a key region to study ice sheet interactions with the wider ocean-climate system. Here, the landform record has largely been used to decipher ice sheet history and to establish whether the British-Irish Ice Sheet or the Irish sector only was advancing or retreating with respect to climate change (McCabe and Clark, 1998; Greenwood and Clark, 2009). Reconstructing the former behaviour of this ice sheet has traditionally relied heavily upon geomorphological interpretations of the glacial landform record. However, recent work on drumlins and ribbed moraines indicates that using the shape of these landforms alone to establish ice flow direction may not be definitive enough, particularly in small study areas (Dunlop and Clark, 2006; Spagnolo et al., 2010). It is therefore essential to consider different approaches that are independent of geomorphology to critically assess previous palaeo ice sheet interpretations. An alternative method is to study the provenance of the sediments in the glacial landscape from which transport direction can then be obtained. This is done by analysing the geochemistry of glacial deposits, which can be used to trace the transport pathways of the sediments across the terrain and help to resolve/confirm regional-scale ice flow patterns in formerly glaciated terrain (Scheib *et al*., 2011; Scheib *et al*., 2010).

Method

Recent research has established that soil geochemistry closely matches the geochemistry of the underlying tills of the former Irish Ice Sheet (Dempster *et al.*, 2013). Soil geochemistry in areas of till can therefore be used to infer till provenance and transport direction. Soil samples that occur on areas of till were selected from the soil geochemical data sets using a Geographical Information System (GIS) that contained GSNI and EPA published superficial geology maps that showed till distribution in the study area. A total of 1888 soil samples that occurred on till were extracted from the Tellus Border survey and 3841 from the Tellus survey. For the main analysis of the Tellus Border data 27 elements were selected (Al_2O_3, As, Ba, CaO, Ce, Co, Cr, Cu, Fe_2O_3, Ga, Hf, K_2O, La, MgO, Mn, Nb, Ni, Rb, Sc, Se, Sr, Th, TiO_2, U, V, Zn, and Zr) and a separate analysis of metals, semi metals and pathfinder elements was also performed using 18 elements (Ag, Al, As, Cd, Co, Cr, Cu, Fe, Mn, Mo, Nb, Ni, Pb, Sb, Sn, Ti, W and Zn). Where both Tellus Border and Tellus samples were combined 23 elements were used (Al_2O_3, As, Ba, CaO, Ce, Co, Cr, Cu, Fe_2O_3, Ga, K_2O, La, Nb, Ni, Rb, Sc, Se, Sr, Th, U, V, Zn, and Zr).

Principal component analysis was applied to the geochemical data as the main investigative tool. This identifies a number of principal components (PCs) that allow identification of groups of related elements that together indicate a mineralogy, which in turn indicate a likely bedrock source material for the till. With reference to bedrock geology maps the likely provenance of the sediment can then be determined and degree and direction of subglacial transport identified. Analyses were performed for the entire Tellus Border survey area, the combined Tellus Border and Tellus survey area and also fourteen sub-sampled regions that represent a range ice flow events defined by published subglacial bedform (drumlin) morphology (lineation flow sets).

Results

The report presents a selection of the most illustrative results with supplementary material included on CD-ROM that contains all results from the analyses performed.

Results in the report include:

- Tellus Border regional analysis.
- Tellus Border metals, semi metals and pathfinder elements analysis.
- Flow set analysis:-
    - Isochronous example.
    - Time transgressive (fluctuating flow) example.
    - Time Transgressive (retreating margin) example.
    - Unknown flow direction example.

Results on the CD ROM include:

- Tellus Border regional analysis: A0 size comparison map sheet, A1 size map sheets for each significant PC.
- Tellus Border metals, semi metals and pathfinder elements regional analysis: A0 size comparison map sheet, A1 size map sheets for each significant PC.
- Combined Tellus Border and Tellus samples analysis: A0 size comparison map sheet, A1 size map sheets for each significant PC.
- Flow set analyses: A1 size map sheets for each significant PC of each flow set analysis.

Conclusions

Analysis of the results from PCA of the soil geochemical data in the study area indicate that there is a strong link between the till and local bedrock at a regional scale, with sharp transition of geochemical composition observed across main lithological boundaries. This pattern is repeated in the analysis of metals, semimetals and pathfinder elements and also at flow set scale in a range of glaciological contexts throughout the region. A main conclusion of the work is that the majority of till deposits in the survey area have been locally derived, meaning that the rate of subglacial transport in this sector of the Irish Ice Sheet was low and that there were low rates of evacuation of subglacial debris to the ice margins. This also means that the geochemistry of the subglacial bedforms in the study area must also reflect the local bedrock, which has implications for competing formational hypotheses of these landforms.

Subglacial transport of material can be detected however at both the regional and flow set scale. Where it is observed the direction of transport is in agreement with the flow directions indicated by bedform geomorphology in the immediate area. No particular glaciological context appears to favour transport but the presence of geochemically distinct rocks adjacent to one another improves identification of the signal. The distance of transport is low within the study area with a maximum distance of approximately 12km recorded.

1. INTRODUCTION

This report details work completed for the Tellus Border research project No. 10761: *A geochemical approach to unravelling ice sheet history using both Tellus and Tellus Border soil geochemical data*. It presents the background, methodology and selected results from the project which was undertaken between April and October 2013 by the Quaternary Environmental Change research group at the University of Ulster at Coleraine. The stated project objectives were:

- Completion of the first investigation of regional geochemistry for the northern sector of the Irish Ice Sheet.
- To investigate former ice flow directions from till provenance.
- To integrate the Tellus Border geochemical data set with the Tellus data set for Northern Ireland.

To achieve these objectives, Principal Component Analysis (PCA) was applied to the Tellus Border soil geochemical data for samples taken on till. Soil geochemistry can be used as an effective proxy for till geochemistry (Dempster et al., 2013) and PCA was used to identify significant element associations that can be linked to the likely parent bedrock material, allowing the provenance of the underlying glacial sediment to be determined. The PCA data was mapped to allow the spatial distribution patterns of the element associations to be compared to published ice flow trajectories based on landform geomorphology. The Tellus Border samples used in this study have been integrated with the equivalent Tellus Northern Ireland geochemical data to produce a full regional picture of glacial sediment provenance for the northern sector of the Irish Ice Sheet.

1.1 BACKGROUND

This section provides background material for the study, detailing the geological and glaciological context.

1.1.1 Geology of the north of Ireland

The north of Ireland hosts a diverse range of bedrock which can be broadly divided into four main domains based on age (Fig. 1) (Mitchell, 2004). The oldest rocks are found mainly in counties Donegal, north central Leitrim and Sligo, Londonderry and Tyrone. They are Meso- to Neoproterozoic age and include the Dalradian Supergroup, which consists of deformed metamorphosed sandstones and mudstones with basic intrusive and extrusive units (Cooper and Johnston, 2004a). Ordovician-Silurian age bedrock is present in counties Louth, Monaghan, Cavan, south east Leitrim, Down and Armagh and is comprised of greywacke sandstone and mudstone turbidite sequences containing numerous minor intrusions (Anderson, 2004). The Tyrone Igneous Complex is Ordovician to early Silurian in age and is composed of volcanic and plutonic rocks with associated marine sediments (Cooper et al., 2011). The Devonian and Carboniferous are mixed siliclastic and carbonate sediment sequences and include significant andesite bodies such as the Barrack Hill Andesite in Co. Tyrone (Mitchell, 2004). Devonian intrusive igneous rocks are represented in Donegal by the Main Donegal, Thorr and Barnesmore granites and the Fanad Pluton, with the Newry Igneous Complex (Cooper and Johnston, 2004b) intruding the Ordovician-Silurian turbidite sequences of counties Down and Armagh. Carboniferous rocks outcrop mainly in north Monaghan, north east Cavan, over most of Leitrim and Sligo, south Donegal, Fermanagh and Armagh, with outliers in Tyrone and Londonderry. The youngest bedrock is the Palaeogene Antrim Lava Group, Mourne Granites and Slieve Gullion intrusive complexes (Cooper, 2004; Cooper and Johnston, 2004c). A rhyolite complex associated with the Antrim Lava Group is located in county Antrim. Numerous Palaeogene dyke swarms and sills are intruded throughout the region (Cooper at al., 2012) and Mesozoic sediments are found exposed primarily around the fringes of the Antrim Plateau and in the Lagan Valley-Newtownards Basin (Mitchell 2004).

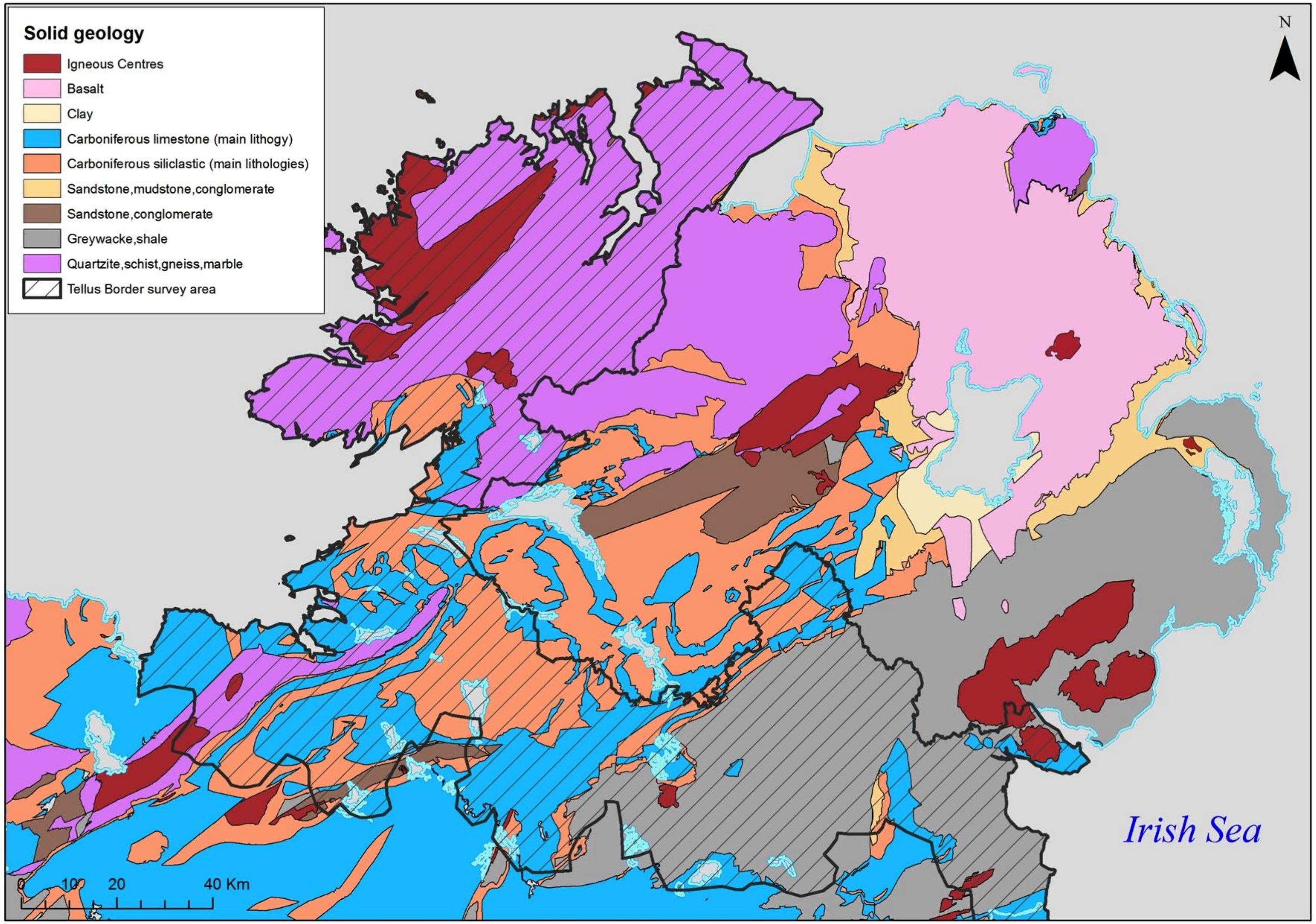

Figure 1. Simplified solid geology of the north of Ireland with Tellus Border survey area shaded.

1.1.2 Primary glacial sediment: till

Regionally, Quaternary glacial deposits mantle the bedrock with till being the most widespread and dominant sediment (Fig. 2) (GSNI, 1991; Fealy et al., 2009). Till is primary glacigenic sediment which forms and is deposited subglacially at the ice-bed interface or traction zone (Benn and Evans, 2010) and therefore directly records or reflects sediment entrainment and transport in this environment. The term till encompasses a wide range of sediment with much textural and structural variation. At the macro scale it can appear massive, matrix or clast supported with the matrix being a combination of sand, silt or mud. The primary source of till is bedrock and previously deposited glacial sediments that become entrained and reworked by ice advance (Dreimanis and Vagners, 1971; Burek and Cubitt, 1991; McClenaghan et al., 2000). Because ice entrains material at its base continually along its flow path, establishing till provenance can be used to infer ice flow directions. Provenance may be investigated through the lithology of clasts within the till or by using its geochemistry. Till will inherit its geochemical characteristics from its parent material (Shilts, 1976) and these characteristics are in turn dependent on the type of source bedrock, its mineral content and its susceptibility to weathering. Soils that develop on till inherit this geochemical signature and it has been established that soil geochemistry in the north of Ireland can be used as an effective proxy for till geochemistry (Dempster et al., 2013). Therefore, the soil geochemical data generated from the Tellus Border and Tellus surveys offers the opportunity to investigate glacial sediment provenance throughout this sector of the Irish ice sheet.

1.1.3 Subglacial bedforms and ice flow direction

Subglacial bedforms, namely ribbed moraines and drumlins, are widespread throughout areas of till in the study area and are most dense in counties Fermanagh, Monaghan, Armagh, Cavan and Leitrim (Greenwood and Clark, 2008). Ribbed moraines and drumlins are predominantly composed of till and their morphology is commonly used in glaciological reconstructions (e.g. Boulton and Clark, 1990; Knight and McCabe, 1997; Dunlop and Clark, 2006; McCabe, 2008; Clark et al., 2012). Using GIS and remote sensing, subglacial landforms are mapped individually then grouped into flow lines, which are then grouped into flow sets. Flow sets then are a way of compiling and visualising the main ice flow directions and pathways for an ice sheet.

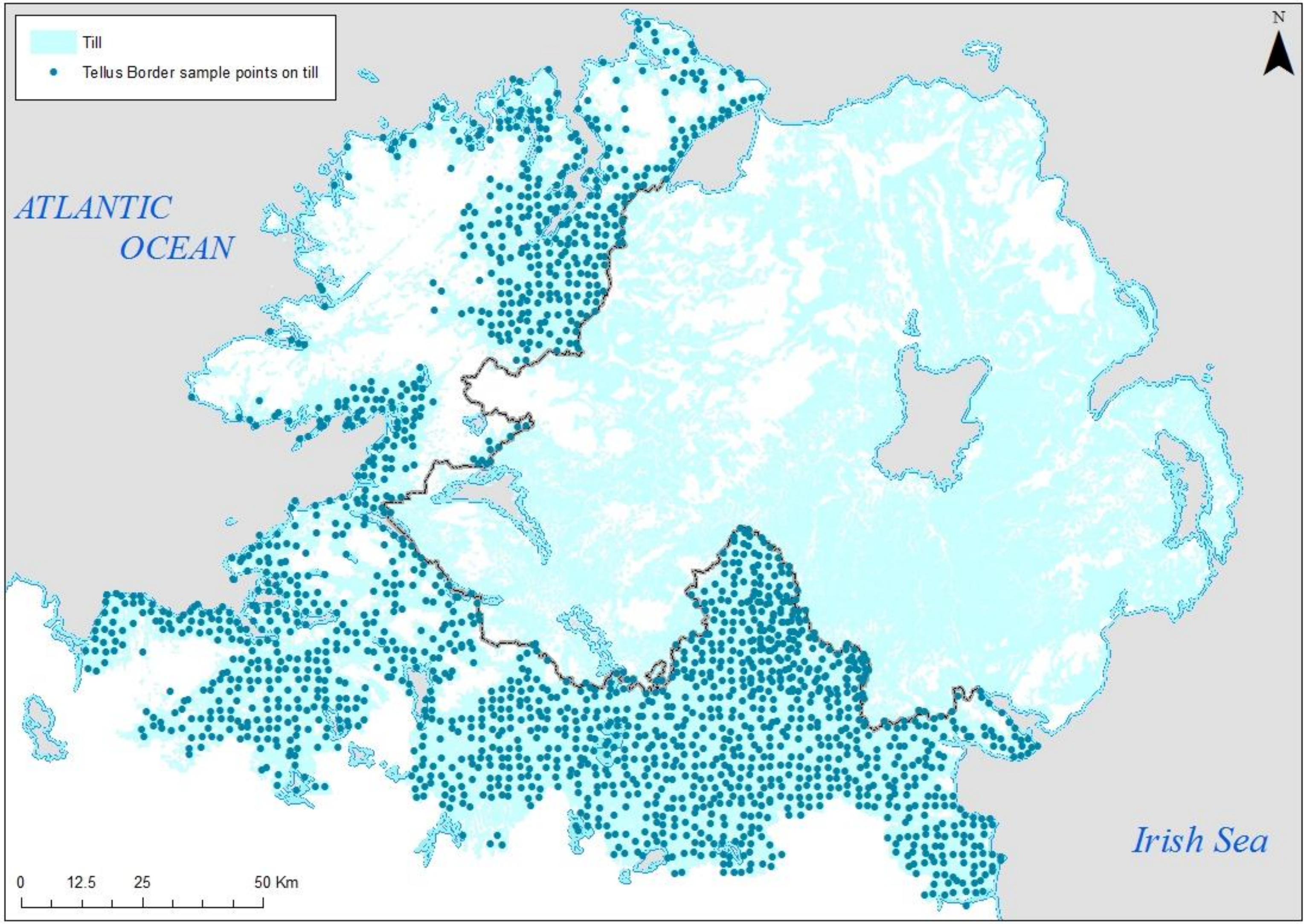

Figure 2. Tellus Border soil sample localities on till with till distribution on the north of Ireland (Fealy et al., 2009; GSNI, 1991)

When grouping flow sets, the following criteria have been suggested (Clark, 1999);

- Parallel concordance – neighbouring landforms have similar orientation.
- Close proximity – landforms are closely packed.
- Similar morphometry – landforms show similar forms.

Flow sets are either interpreted as time transgressive or synchronous. Synchronous flow sets are formed at the same time i.e. a sustained flow direction and have well developed parallel concordance and similar morphometry over small areas and gradual changes exhibited over larger areas. Time transgressive sets form when ice flow patterns change e.g. behind a retreating ice margin, so have lower parallel concordance, varying morphology and exhibit cross cutting (Clark, 1999). Recent research has extensively mapped the ribbed moraines and drumlins of Ireland and grouped them into flow sets (Greenwood and Clark, 2008; 2009a, 2009b). The area covered by the Tellus Border and Tellus surveys contains both isochronous and two types of time transgressive drumlin (lineation) flow sets, along with those which have an unknown glaciological context (Fig.3). The study area therefore offers the opportunity to investigate subglacial sediment provenance both in a regional setting and also in a range of glaciological contexts.

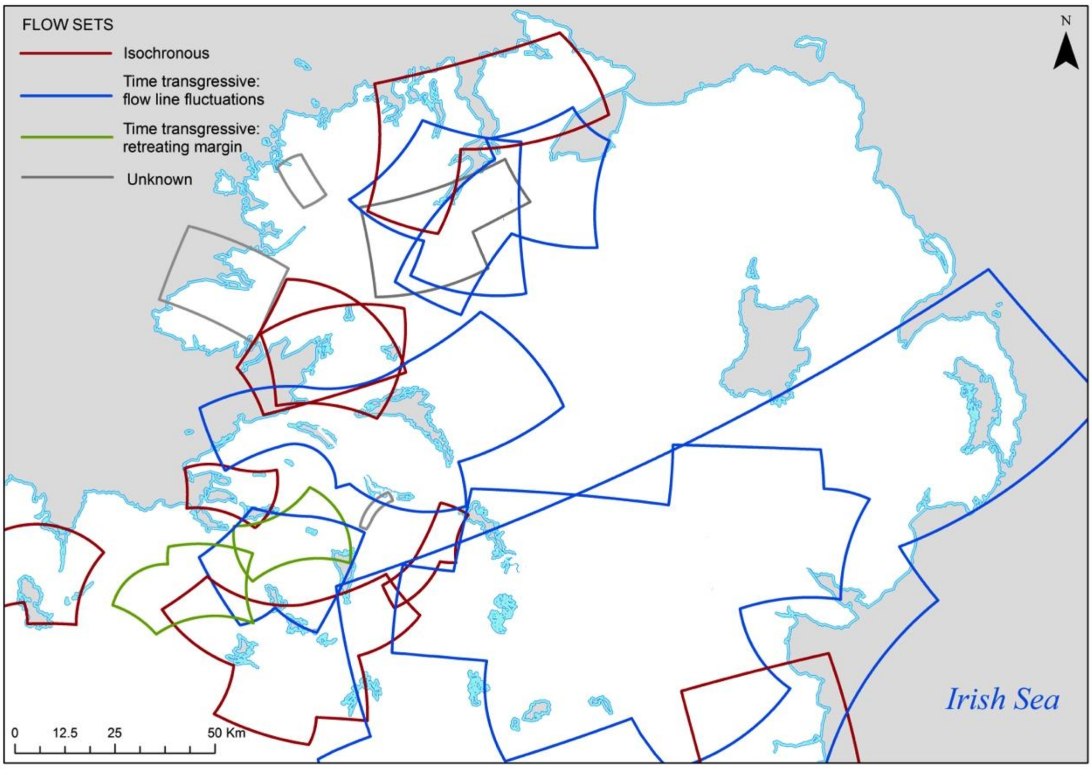

Figure 3. Glacial lineation (drumlin) flow sets in the Tellus Border survey area, including those with a cross border aspect. After Greenwood and Clark, 2009b.

2. METHODOLOGY

This section details the methodology used in the project, including sample selection, data preparation and analysis.

2.1 Sample selection

Geochemical data for a total of 3556 soil samples from the Tellus Border survey were received from the client (GSI) at project commencement. The first stage in preparing the data for analysis was selecting the most appropriate samples from the data set. A number of selection criteria were applied beginning with exclusion of soils with Loss on Ignition (LOI) values of >50%, as organic soils such as peat are reducing environments that can concentrate certain elements as they are sinks for atmospheric and other environmental pollution. This first step removed 912 or 25.64% of the samples (Table 1).

The data for the remaining 2644 was then imported into a GIS to select only those samples that occurred on tills. The Environmental Protection Agency 1:50,000 scale sub soil maps were downloaded (http://gis.epa.ie/DataDownload.aspx) and the areas mapped as till were extracted to produce a map of till distribution in the survey area (Fig. 2). The total area of till cover is 6249.72 km^2 and the distribution map was used to select the appropriate samples in GIS. This returned 1888 samples for analysis which represents 53.09% of the total Tellus Border soil sample load.

Further sub selections of samples on till were taken based on published glacial lineation (drumlin) flow sets, either wholly or partly within the Tellus Border area (Fig.3). A total of 22 lineation flow sets are found within the survey area, fourteen of which have n>50 so are best suited to PCA and therefore most informative to this investigation (Fig.4). Three flow sets have n<10 which is too low to perform PCA, and five of the flow sets have sample numbers n<50 so that the statistical outputs from PCA are not as robust as those with n>50.

Table 1. Tellus Border sample selection statistics. Only those that have LOI <50% and occur on till are used for analysis.

	Number	% of total Tellus Border samples
Tellus Border samples	3556	100
Samples >50% LOI	912	25.64
Samples on till	1795	53.09

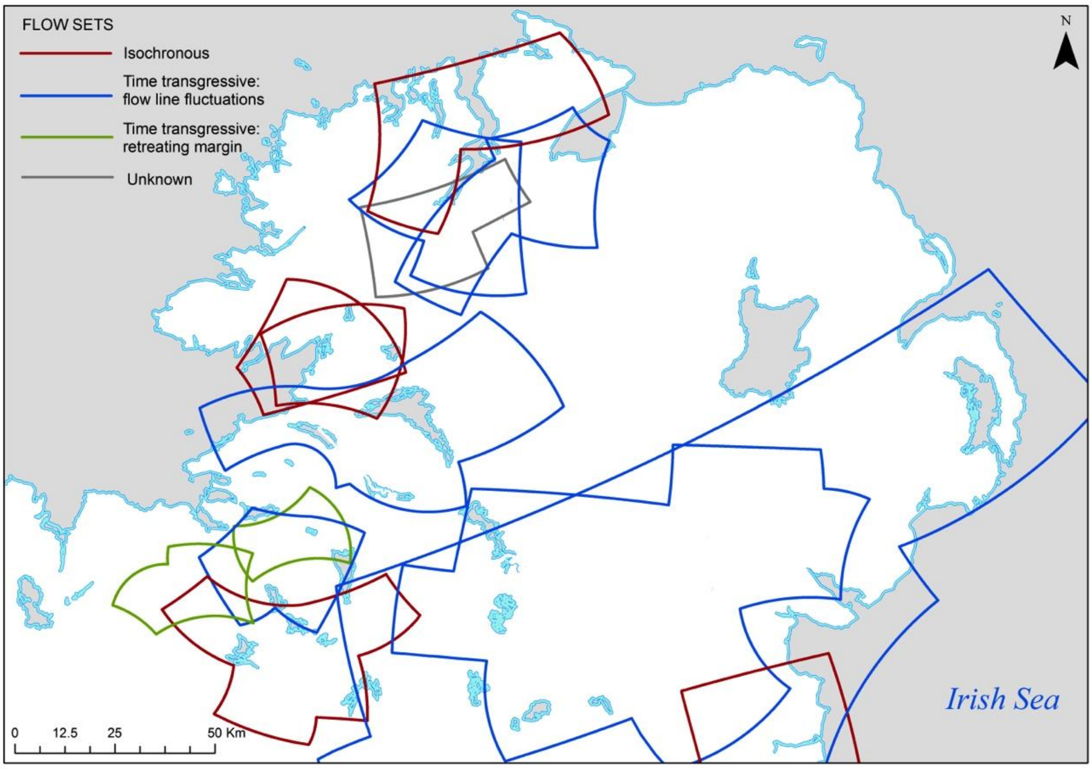

Figure 4. Glacial lineation (drumlin) flow sets with sample numbers >50 that are used in this study.

2.1.2 Data preparation

Element data from laboratory analysis was reported as individual element concentration values, so in order to aid analysis and also allow improved comparison to work already completed using the Tellus project 'A' soil data in Northern Ireland, oxide equivalents were calculated for Al, Ca, Fe, K, Mg, and Ti from their reported values. A total of 28 elements were used for work already completed for the Tellus data, so the data for these elements were also selected from the Tellus Border data set. However, there is no reported values for Si in the Tellus Border data so the element list selected for PCA consists of the 27 elements Al_2O_3, As, Ba, CaO, Ce, Co, Cr, Cu, Fe_2O_3, Ga, Hf, K_2O, La, MgO, Mn, Nb, Ni, Rb, Sc, Se, Sr, Th, TiO_2, U, V, Zn and Zr. Concentration values for these elements were then log transformed prior to analysis as PCA is sensitive to non normalised data (Pison et al., 2003).

2.1.2 Analysis: PCA

PCA is a multivariate statistical technique commonly used to investigate variability in large geochemical data sets (Grunsky and Smee, 1999; Cheng et al., 2006; Scheib et al., 2011). It is a variable reduction method that produces a smaller number of artificial variables, called Principal Components (PCs). Each PC represents a certain amount of variability in the data and the first two PCs usually account for most of the variation within the whole data set, though as it is an orthogonal procedure each PC contains information about the data. When using PCA only those PCs with eigenvalues >1 are used as they account for the majority of the variance in the data set used.

PCA produces eigenvectors, also referred to as principal component coefficients or loadings, which describe the relative significance of a component i.e. chemical element and its variability within the data set and are used to automatically calculate scores for each PC. The element loading values determine a sample point's score, so that grouping of high loading elements give high scores and grouping of low loading elements give low scores. A sample point's score therefore reflects the element groupings and in this study it is these groupings that can be linked to possible bedrock sources. The amount of eigenvectors calculated will be equal to the number of variables used, which in this study is the number of chemical elements. The PC scores were imported into the GIS to enable visualisation of the spatial distribution of the linked element groupings and their relationship to solid geology.

2.1.4 Joining the Tellus Border and Tellus soil geochemical data sets

Data conditioning for the Tellus and Tellus Border project surveys was undertaken before the data was released. The two survey areas are contiguous and although they used the same method of soil sampling and share a geochemical determination method (ICP-MS) they are separated by time. It was important therefore to determine if a data levelling exercise was required. The concentration values for each element used for PCA were mapped individually using a GIS in order to identify how data for the two survey areas compared. No levelling exercise was necessary as the majority of the elements matched across the surveys, although four elements were identified for removal before analysis (Mg, Mn, Ti and Hf). The lower limits of detection were different for each survey area for these elements, leading to under or over reporting on either side of the Northern Ireland border. Therefore a total of 23 elements were used in the analyses that used both Tellus and Tellus Border data.

3. RESULTS

PCA has been performed on all the data for soils sampled on till at survey wide and flow set scale where n>10. The Tellus Border and Tellus data have also been amalgamated to provide regional wide and cross border flow set analyses. The number of significant PCs (eigenvalues >1) across this data is between four and seven and for the purposes of this report all the significant PCs are presented for the regional samples on till analysis. Results for the flow sets are detailed through examples of isochronous and time transgressive types, with only the most informative PCs presented. The full results are included in PDF format as summary and individual maps for all the regional and flow set analyses on the CD-ROM that accompanies this report.

3.1 Tellus Border regional results

This section presents the regional results for the PCA of upper (A) soil samples taken on till areas of superficial geology for the whole of the Tellus Border survey. The maps presented show the PC score distribution for the six Principal Components with eigenvalues >1 (Fig. 5) with the simplified regional geology. The scores are represented by a divergent colour scheme with orange to red representing increasingly positive scores and light to dark blue increasingly negative scores. Each dot represents a single sample point and individual colours equate to a score range for each PC, but as the data is not normally distributed the score ranges are not equal number increments across the maps.

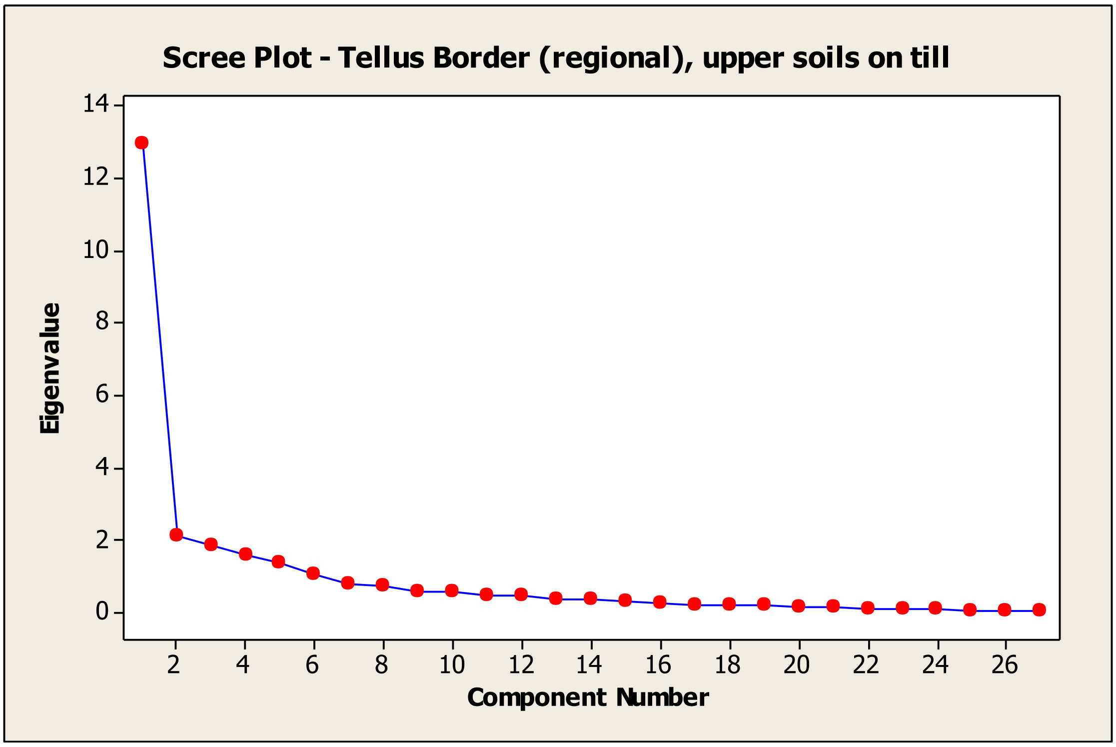

Figure 5. Scree plot of Principle Component eigenvalues for upper soil samples taken on areas of till superficial geology in the Tellus Border survey area. A scree plot shows the eigenvalues (y-axis) of the principal components (x-axis) for the data set in descending order and indicates the relative importance of the PCs. Those PCs with eigenvalues <1 account for an increasingly small and insignificant amount of the variance in the data so are not used. In this study the first five PCs have eigenvalues >1 so are the most significant for the data set.

3.1.1 Principal Component scores: Tellus Border soils on till

There are six principal components with eigenvalues >1 for the Tellus Border soils on till regional data, that together explain 77.3% of the variance. Principal Component 1 (PC1) represents 47.9% of the variance in the data and highest loading elements (≥0.235) are Al_2O_3, Co, Cr, Ni, Fe_2O_3, Sc, and Ga (Fig. 6). High scores associated with these elements are observed concentrated in the south east of the survey area in close association with greywacke and shale (Fig. 7). High scores are also observed in south and central to north Donegal. No negative loadings are recorded, but the lowest loading elements (<0.1) are CaO, U, TiO_2, Sr and Se with lowest scores found in north county Monaghan, central Cavan, south east Leitrim, south and north Sligo and south Donegal. These are areas of Carboniferous rock sequences with limestones as a major or minor component. The low scores observed in central and north Donegal do not all occur directly on limestones, though limestones do outcrop and the schists in the region are calcium rich.

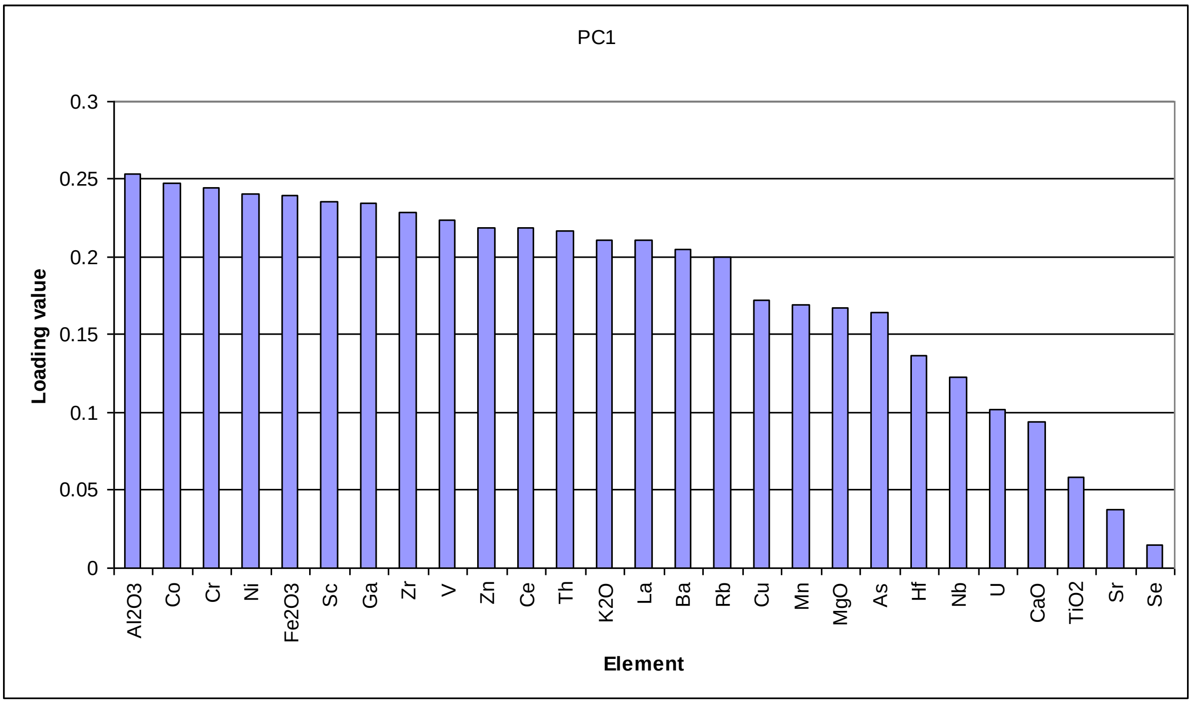

Figure 6. Element loadings for Principal Component 1, A soils on till in Tellus Border area.

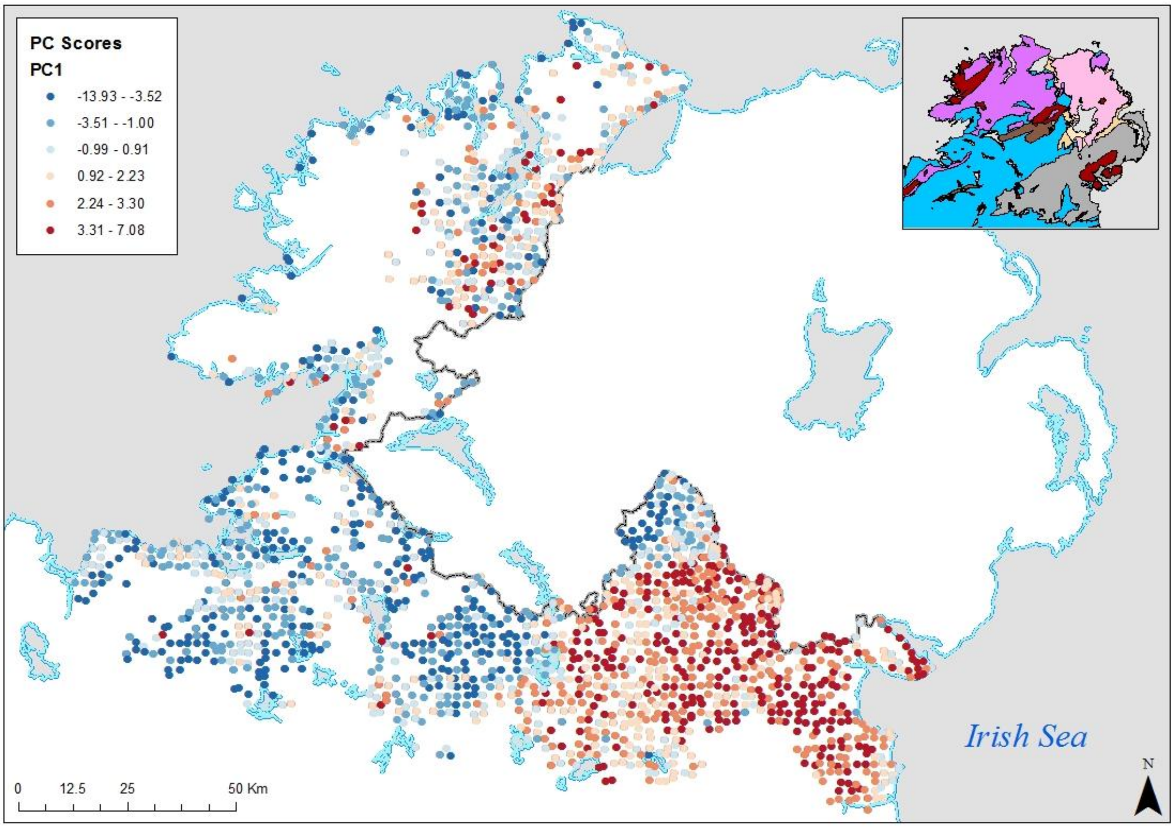

Figure 7. Principal Component 1 Score distribution for Tellus Border 'A' samples taken on areas of till superficial geology. Insert shows simplified bedrock geology - see Figure 1 for key.

PC2 (7.8% of variance) has highest loading (>0.18) elements are Se, U, Sr, CaO and As (Fig.8) with high scores found in north to north-west and south Monaghan, north-east and west Louth, central and north-western Cavan, over most of Leitrim, through much of Sligo, and central to north Donegal (see summary map on CD-ROM). These areas contain mud rich bedrock with limestones. The lowest loading elements (<-0.11) are Al_2O_3, K_2O, Ga, Cr, Rb, and MgO with low scores associated with these elements are predominant in the south-east of the study area in close association with greywacke and shale in counties Monaghan, Louth and Cavan. Low scores are also found in close association with Devonian clastic sediments outcropping in south Sligo.

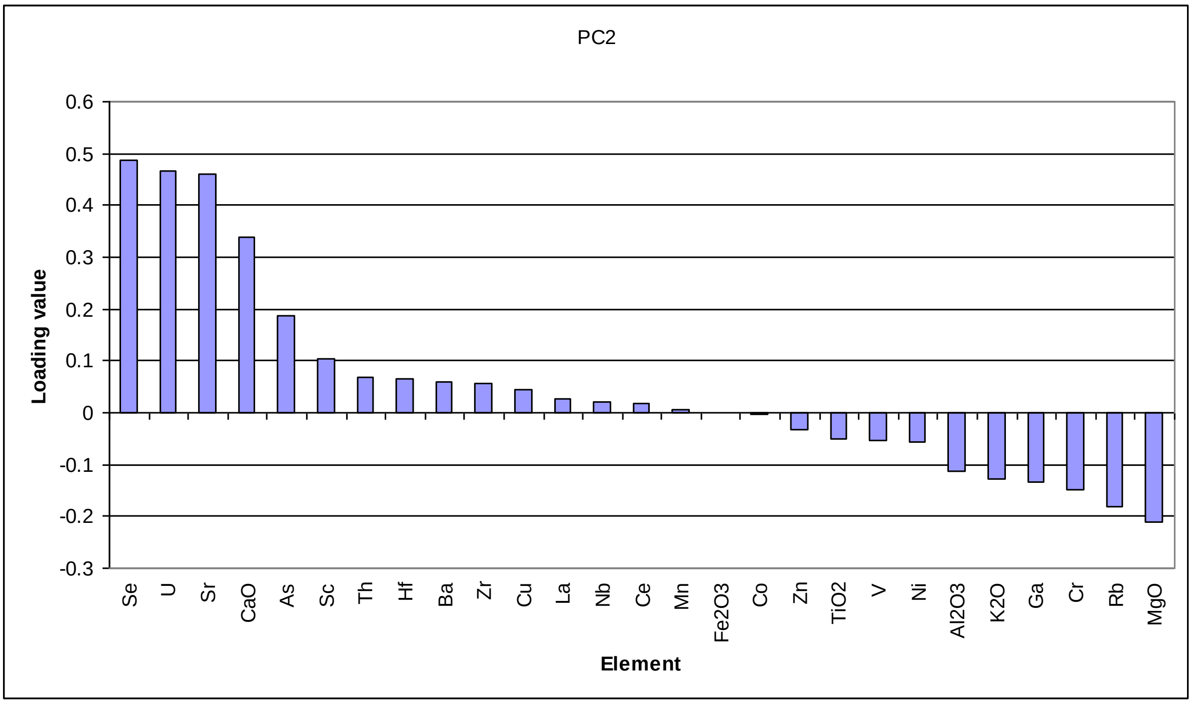

Figure 8. Element loadings for Principal Component 2, A soils on till in Tellus Border area.

PC3 represents 6.8% of the variance and the highest loading elements (>0.23) are Nb, TiO_2, Sr and La (Fig. 9). High scores associated with these elements are in north-east county Louth, central and north Monaghan, in a 'u' shape in southern Cavan and the north-west of the county, west Sligo and throughout county Donegal (see supplementary material CD-ROM). The lowest loading elements (<-0.15) are Co,

Fe_2O_3, Zn. Ni, As and Mn with low scores found in north and east Monaghan, south Louth, west Cavan, south and central Leitrim and central and eastern regions of Sligo. A small area of low scores is also observed in south Donegal.

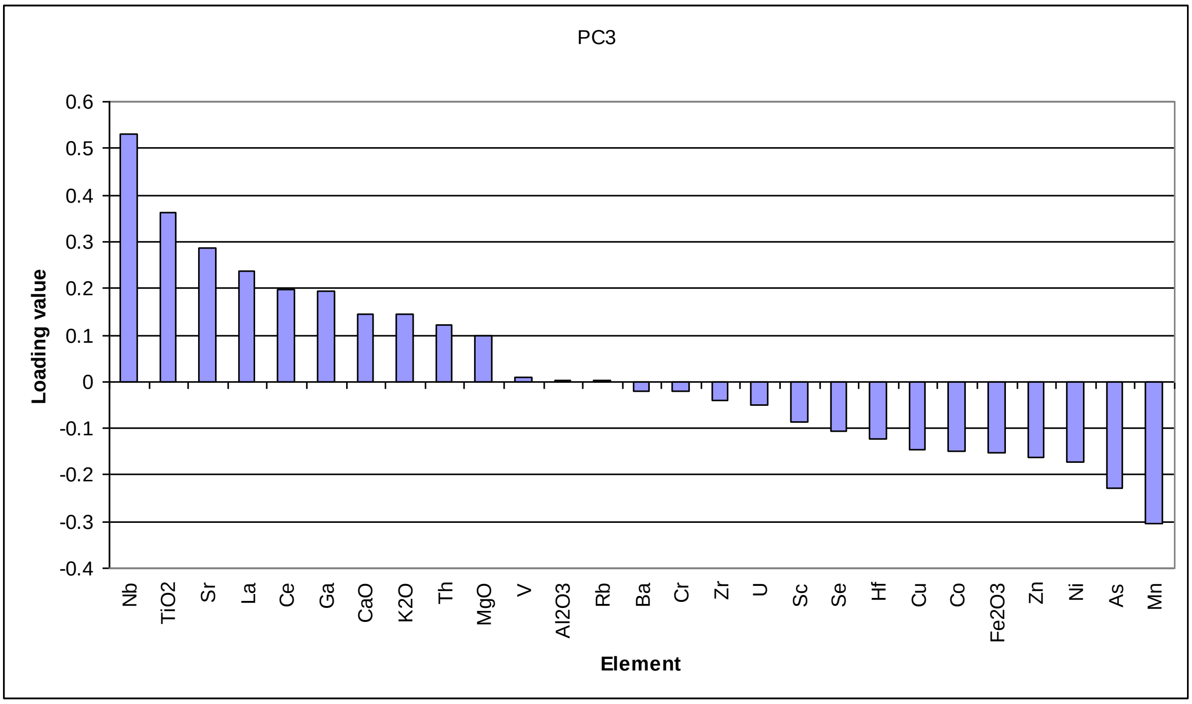

Figure 9. Element loadings for Principal Component 3, A soils on till in Tellus Border area.

PC4 accounts for 5.8% of the variance in the data. Highest loading elements (≥0.199) are TiO_2, V, CaO, Cu, Cr and Ni (Fig. 10) and high scores are found in north-east Louth, north-west and central Monaghan, in a 'u' shape in southern Cavan and also in west Cavan continuing into south Leitrim, central and north Leitrim, central and west Sligo, and in north Donegal (Fig. 11). Lowest loading (<-0.24) elements are K_2O, La, Ce and Th with concentrations of low scores in south Louth, north-east Monaghan, central and north-west Cavan, west Sligo and south and central Donegal.

PC5 (5.2% of variance) has highest loading (>0.17) elements Se, U, Cu, TiO_2 and V (Fig. 12) with high scores associated with these elements found in north Louth, north west and central to south Monaghan, east and north west Cavan, central to north Leitrim, east and west Sligo and for the majority of sample points in Donegal (see supplementary material CD-ROM). Lowest loading (<-0.13) elements are Zr, Ni, Hf, Sr and CaO with low scores recorded over much of Louth, north, central and south Monaghan, central Cavan, south Leitrim and south and central.

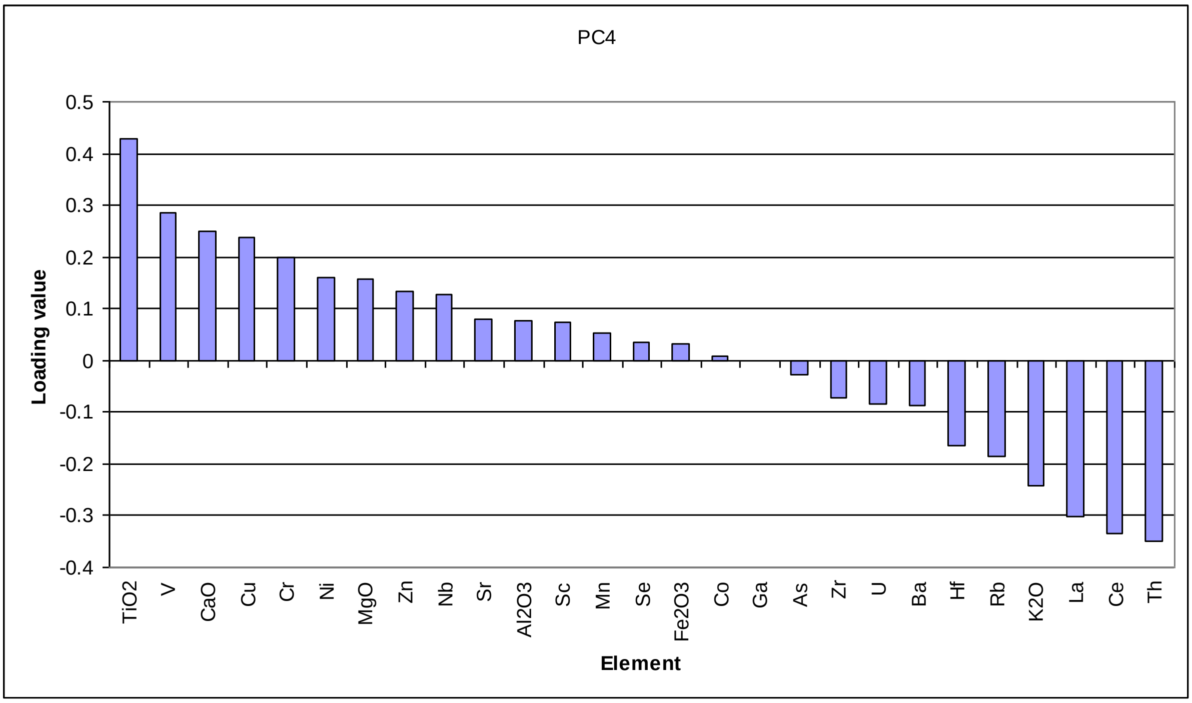

Figure 10. Element loadings for Principal Component 4, A soils on till in Tellus Border area.

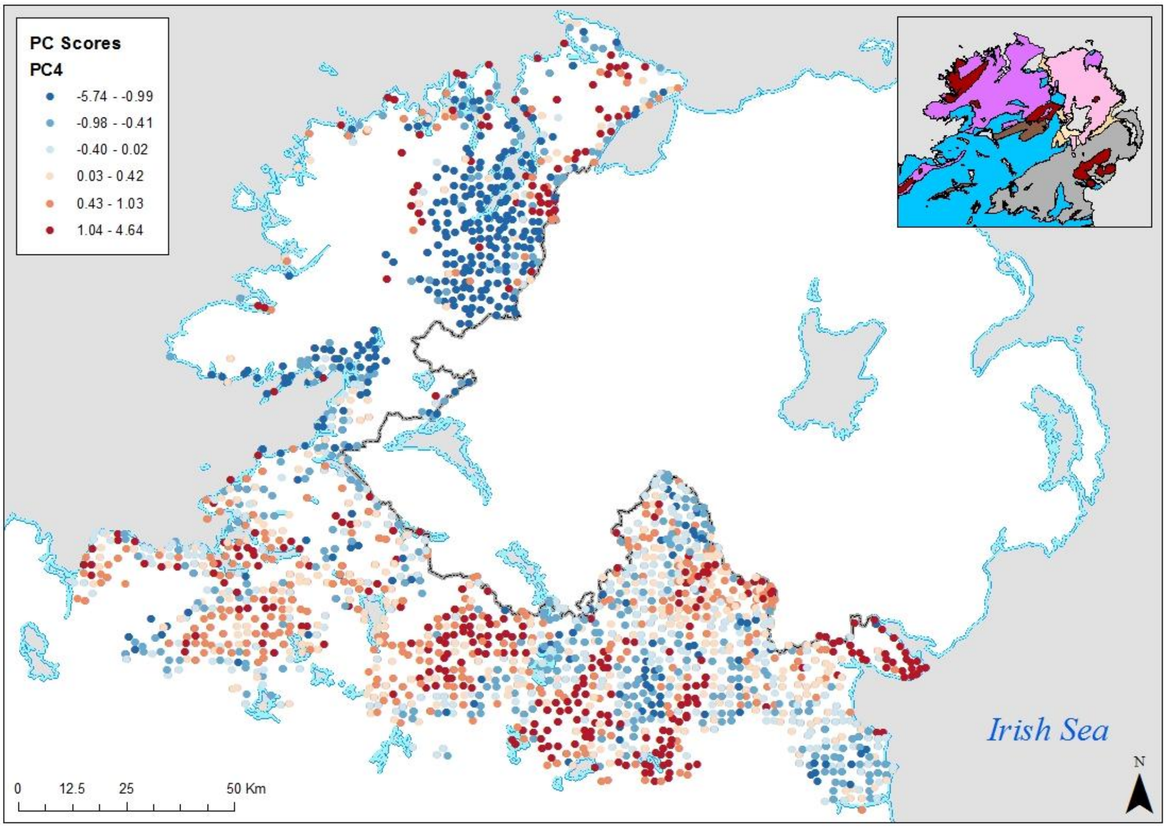

Figure 11. Principal Component 4 Score distribution for Tellus Border 'A' samples taken on areas of till superficial geology. Insert shows simplified bedrock geology - see Fig.1 for key.

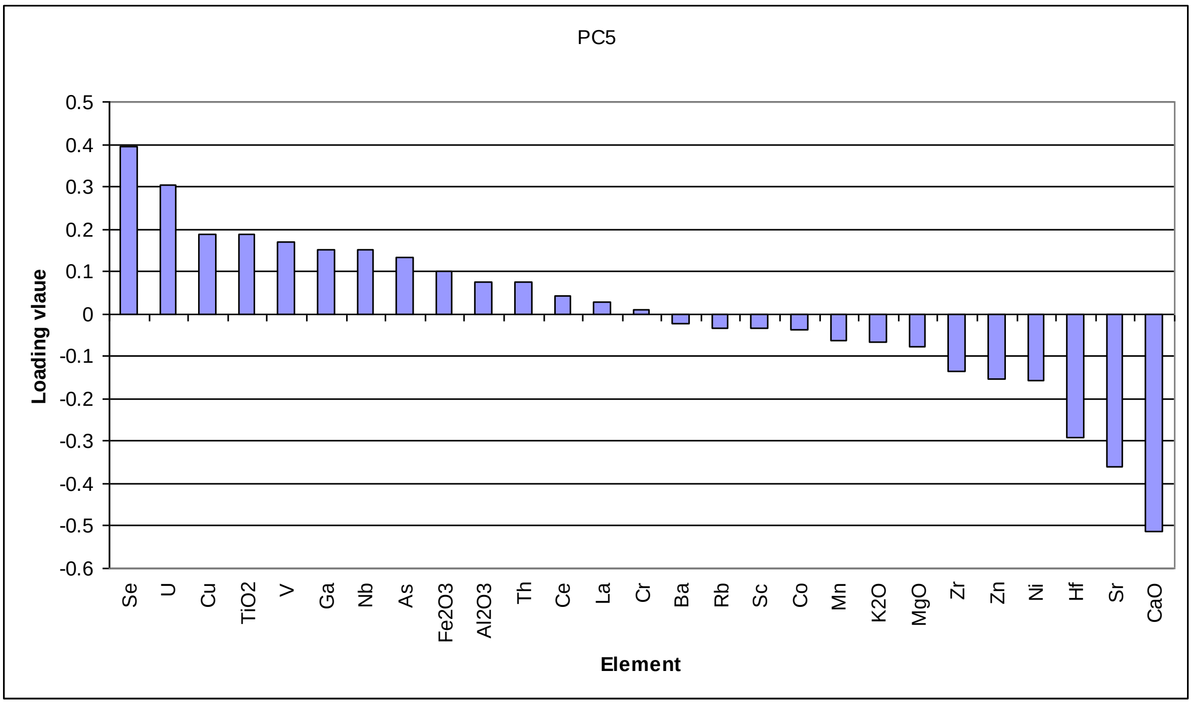

Figure 12. Element loadings for Principal Component 5, A soils on till in Tellus Border area.

PC6 accounts for 3.9% of the variance in the data and the highest loading (>0.2) elements are Hf, Zr, Ba, Se and Sc (Fig. 12). High scores associated with these elements are observed over much of county Louth, north and south Monaghan, north central and north west Cavan, Leitrim, and south Donegal with scattered high scores in east and west Sligo and central to north Donegal. The lowest loading elements (<-0.16) are Co, La, Ce, Zn, As and Mn with low scores recorded in north Louth, east and south Monaghan, over most of Sligo, south Donegal and in central and north east Donegal.

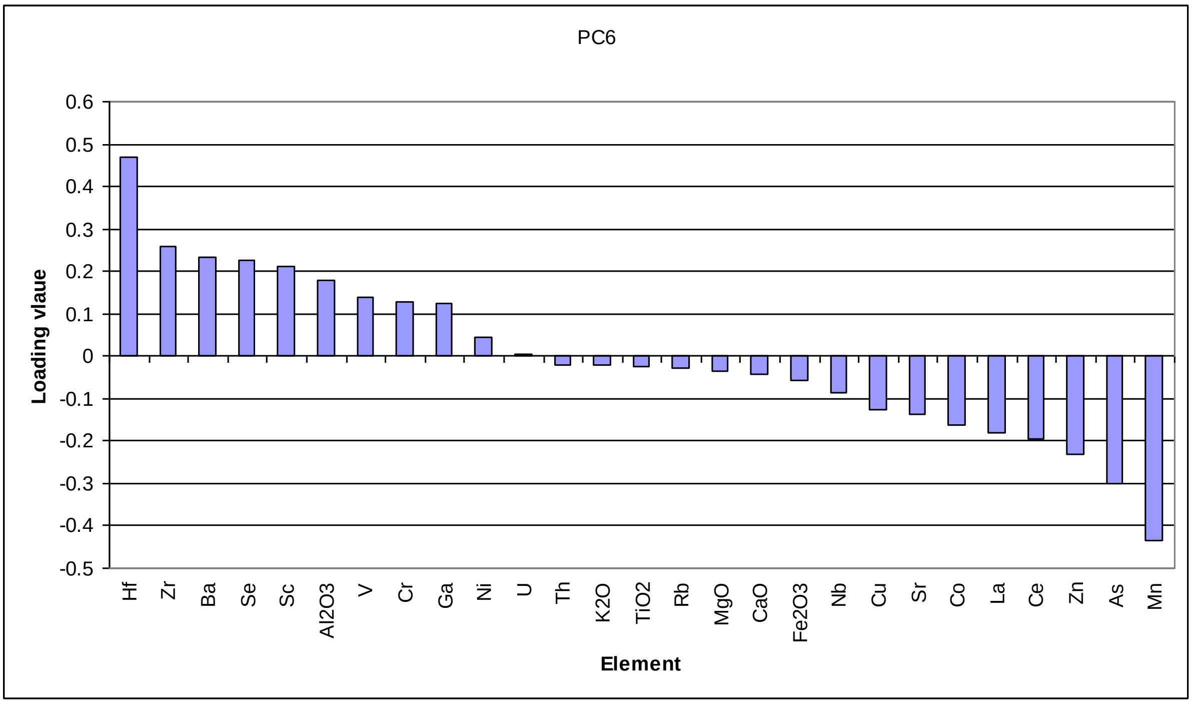

Figure 13. Element loadings for Principal Component 6, A soils on till in Tellus Border area.

3.1.1.2 Interpretation of Tellus Border regional PCA results

The overall interpretation of the regional analysis is that there is a very strong link to local bedrock. In PC1 high loading of Al_2O_3 and Fe_2O_3 suggests clay mineral rich material and associated high scores conform to outcrop of greywacke and shale in the southeast. The other concentration of high scores is in the northwest on Proterozoic meta-sediments that contain a significant proportion of pelite and semi pelite. The high loading group of Co, Cr, Ni and Fe_2O_3 would suggest igneous material and though no significant outcrops occur in the high scoring areas, the greywacke and shale of the south east does however contain much bentonite and volcaniclastic material which may explain the high loading of these elements. The low score distribution (CaO, U, TiO_2 and Sr) conforms to bedrock boundaries also, to areas of limestone or Ca rich bedrock (CaO and Sr) and the metamorphic sediments of Donegal (U, TiO_2 and Se).

PC2 also demonstrates a close link to bedrock boundaries with the low loading element group Al_2O_3, K_2O, Ga, Rb and MgO indicative of clay minerals, and the associated low scores are concentrated in the south-east on greywacke and shale. In south Sligo low scores are found on a limestone dominated area to the north of

Devonian sediments, so may indicate glacial transport of between 3 and 7km to the north. Similarly in north-east Sligo, low scores on limestones are observed to the north of Proterozoic pelitic rocks of the Slishwood Division, again indicating northward movement of clay rich material by approximately 5km. High scores correspond well to areas of Carboniferous limestone (Sr, CaO) and both Carboniferous and Proterozoic sandy rocks (Se, U) in the west of the study area. A sharp transition between scores is observed across the boundary of the Carboniferous limestone and greywacke and shale bedrock of Monaghan, Cavan and Louth.

For PC3 high scores concentrate in particular over much of the metamorphic sediments of Donegal and the high loading of Nb and TiO_2 in this area likely reflect metamorphic minerals such as rutile. High scores around the Carlingford/Slieve Gullion igneous centres likely also reflect metamorphic minerals, with samples taken on the Carlingford pluton likely directly reflecting the igneous rock. In south Donegal high scores are observed over Carboniferous sediments, which suggests transport of meta-sedimentary material over the area of up to 8km. The other high loading elements (Sr and La) are lithophiles that occur in many rock-forming minerals such as feldspar and biotite, so may also explain the high loading in south Donegal on shales. The concentration of high scores in southeast Cavan is anomalous in that the majority of samples on the same bedrock lithology exhibits mid scores that indicate a clay mineral signature (MgO, V, Al_2O_3, Rb, Ba) which is consistent with the greywacke and shale. The greywacke and shale have been metamorphosed though not to the extent that the Proterozoic rocks are and the only igneous body (Crossdoney Granite) is relatively small and on the western margin of the high scoring area, so this concentration may reflect mineralisation. Low scores (loading group Fe_2O_3, Zn, Ni, As and Mn) is consistent with clay minerals and carbonates and the low scoring is observed on limestones, sandstones, greywacke, shale and mudstones. This group is also indicative of mineralisation and low scores are observed in east Monaghan south-east of Clontibret near Castleblaney.

In PC4 high loading of TiO_2 and V indicates muddy sediments with CaO indicating limestones or carbonates and high scores plot on suitable lithologies throughout the study area. The grouping of Cu, Cr and Ni would indicate basic igneous material or mineralisation, and though in this case it is most likely a reflection of shales and mudstones for most high scores, on and around the Carlingford igneous centre and in east Monaghan (close to Clontibret) it is likely related to mineralisation. In Cavan and Monaghan high scores plot in close association with the Gilnahirk Group/Red Island Formation of the Down-Longford Terrane, both on its outcrop and to the south-east. This may represent glacial transport in this direction, though as the rocks of the Down-Longford Terrane contain shales throughout it is perhaps difficult to say for certain with the regional results alone. A second band of high scores trending north north-east/south southwest is found in the eastern side of the county that does not appear to follow a lithological boundary as in the Gilnahirk Group example, so may suggest mineralisation in this area. An area of high scores is observed in northeast Donegal that, although indicative of the bedrock it is located on (Southern Highland Group), represents a sharp transition from low scores to the south (Aghyaran Group) that does not coincide with a bedrock boundary. This may be an intraformational feature or material has been transported north at least 6km from the Aghyaran Formation masking the Southern Highland Group signal. The low loading elements Ce and Th can indicate either felsic igneous material or metamorphosed mud rich sediments and in combination with K_2O and La the latter is most likely, so the dominance of low scores on the Proterozoic rocks of Donegal is consistent with bedrock. Low scores are found on the Carboniferous rocks in south Donegal which indicate transport of material from the surrounding area over these rocks. The low scores in Cavan and Louth are also consistent with the greywacke and shale bedrock of these areas.

The high loading element group in PC5 (Se, U, TiO_2 and V) indicates siliclastic or felsic rocks and the distribution of high scores reflects this for the Carboniferous and Proterozoic meta sediments in the study area, and also on and around the Carlingford igneous centre. High scores are found on limestones in north Sligo that may indicate transport of up to 9km northwest from Proterozoic bedrock that outcrops in the central part of the county. High scores are also found on the Carboniferous limestone in south Donegal and likely represent movement of Proterozoic material over the area. In east Cavan and south Monaghan high scores are found on the quartz rich rocks from the Central Belt of the Down-Longford Terrane. Low loading of CaO and Sr suggest limestones or carbonates and low scores plot in close association with Carboniferous limestones and also the greywacke and shale in Louth. The rocks here are part of

Hawick Group of the Down-Longford Terrane, which have a high, carbonate content and the scores follow the boundary of the Group remarkably closely.

The high loading element group in PC 6 is Hf, Zr, Ba, Se and Sc. Zr is found in higher quantities in greywacke and other sandstones than in mud and limestones and its high loading is reflected in the score distribution with high scoring areas corresponding to greywacke and sandstone bedrock regions. Zr and Hf have a close chemical association, which explains the high loading of Hf. Ba is generally enriched in shales, Se can replace sulphur in diagenetic pyrite of fine-grained sediments and Sc is generally found in higher quantities in fine-grained rocks, so these elements also reflect the bedrock. An area of high scores is recorded in south Leitrim on muddy limestones, these scores may reflect the siliclastic component of the limestone or represent transport of sandstone material from the north. Similarly, in southeast Sligo high scores on limestone may represent glacial transport of sandstone from the east (Carboniferous siliclastics) or south (Carboniferous and Devonian silicastics). The low loading element group (Co, La, Ce, Zn, As and Mn) correlates well with limestone-dominated regions in the south of the study area. No obvious carbonate signal is observed i.e. CaO and Sr, though Mn can be an important component of carbonate minerals. Low scores are also observed over much of Donegal, and in south Donegal there is a sharp contrast between the high scores on mud and sandstone to the northwest and the low scores on limestone to the southeast. The lowest loading elements Zn, As and Mn would also suggest mineralisation in country rock, and a concentration of low scores is found in east Monaghan, to the south-east of Clontibret and north-east of Castleblaney. The low scores to the south and east of the Carlingford igneous complex are found primarily on limestone but their proximity to the igneous body may also be related to mineralisation.

3.1.2 Principal component scores: metallic elements, Tellus Border soils on till

Metallic elements can be dispersed from their source rocks by glacial processes (e.g. Parent et al., 1996). Dispersal plumes from potential ore or mineral bodies can be detected using geochemistry, so the metallic elements reported in the Tellus Border soil geochemical data set were analysed separately to determine if they have been glacially dispersed within the study area, which may be of interest to the minerals industry. Eighteen elements were used for the analysis, including 'pathfinder' elements and semimetals (Ag, Al, As, Cd, Co, Cr, Cu, Fe, Mn, Mo, Nb, Ni, Pb, Sb, Sn, Ti, W and Zn).

Three PCs have eigenvalues >1 that combined explains 63.1% of the variance. PC1 accounts for 43.5% of the variance in the data and the highest loading elements (>0.3) are Co, Ni, Fe and Zn (Fig.14). The majority of high scores associated with these elements are observed in the south east of the study area in close association with greywacke and shale, with highest scores concentrated in north Louth, east to south Monaghan, continuing southwest into county Cavan (Fig. 15). High scores are also found in central to northeast Donegal and scattered through Leitrim and central Sligo The lowest loading elements (≤0.17) are Ag, Cd, Mo, Nb, Ti and W with low scores recorded for north Monaghan, northwest Cavan continuing into south-east Leitrim, south and west Sligo and south and central Donegal.

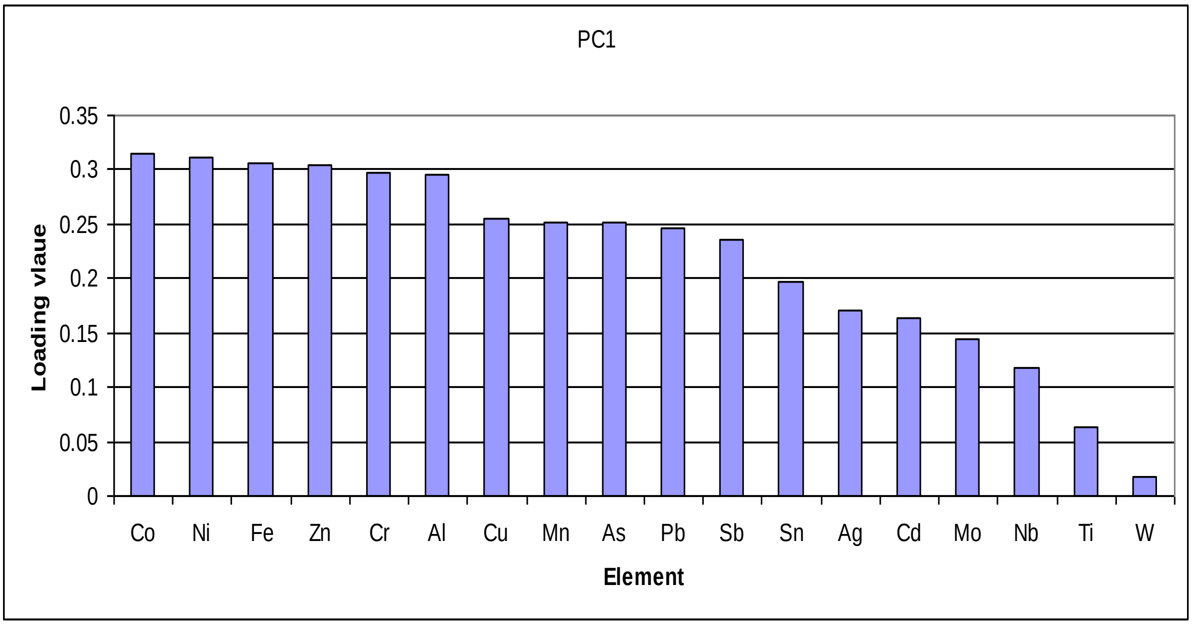

Figure 14. Element loadings for Principal Component 1, metallic and pathfinder elements on till in Tellus Border area.

PC2 (11.5% of variance) has highest loading (>0.15) elements Mo, Cd, As, Pb and Ag (Fig. 16). High scores associated with these elements are observed in mid to south Louth, in north and east to south Monaghan, northeast Cavan, throughout Leitrim and Sligo and in central to north Donegal (Fig. 17). The lowest loading (<-0.13) elements are W, Al, Cr, Ti and Nb with low scores recorded for north Louth, mid Monaghan, east Cavan and central to north Donegal.

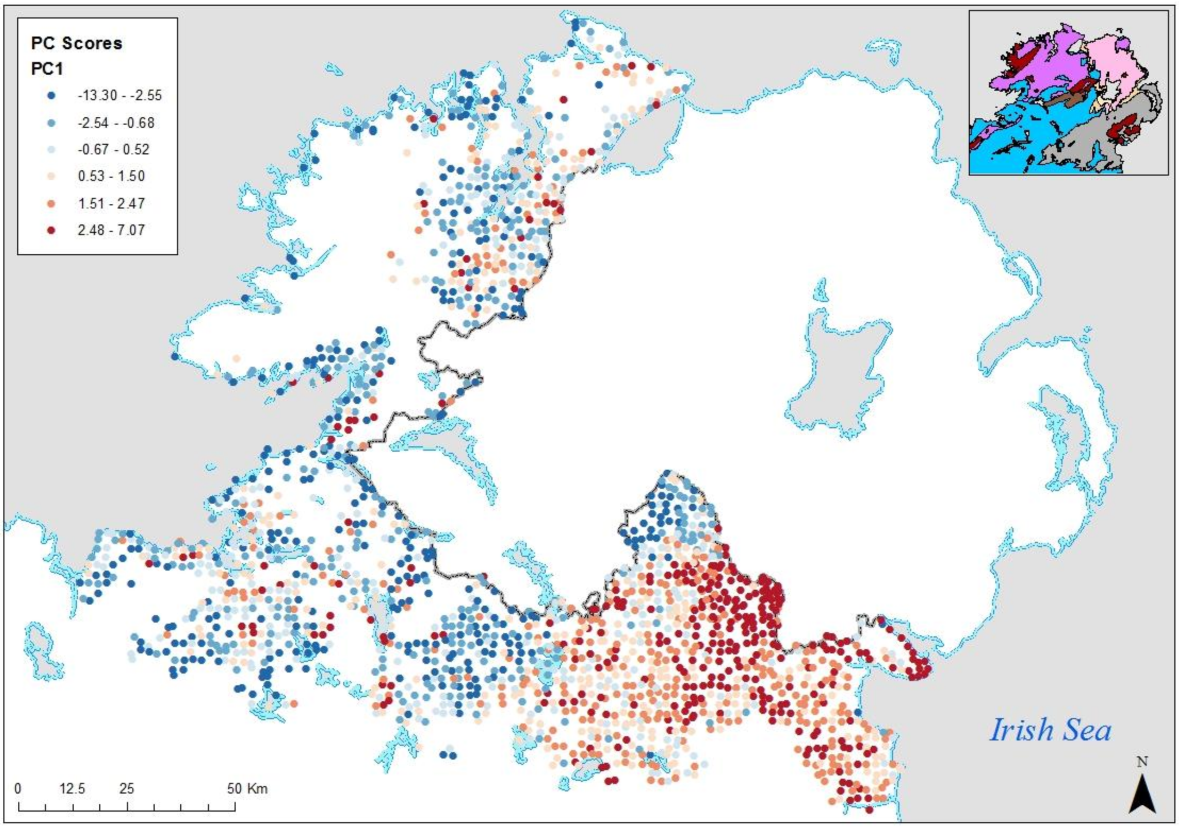

Figure 15. Principal Component 1 Score distribution for metallic and associated elements in the Tellus Border on areas of till superficial geology. Insert shows simplified bedrock geology - see Fig.1 for key.

PC3 represents 8.1% of the variance in the data and has highest loading (>0.16) elements Ni, Co, Fe, Mn and Cr (Fig. 18). High scores are found in south to central Louth, in a southwest trending band extending from north Monaghan into central Cavan, west and north Sligo, and south and north Donegal (Fig. 19). The lowest loading elements (<-0.3) are Sn, Ti, Nb, W and Ag with low scores recorded in north Louth around the Carlingford and Slieve Gullion igneous complexes, east Monaghan, southeast and northwest Cavan, central and north Leitrim, north central Sligo, and central to north Donegal.

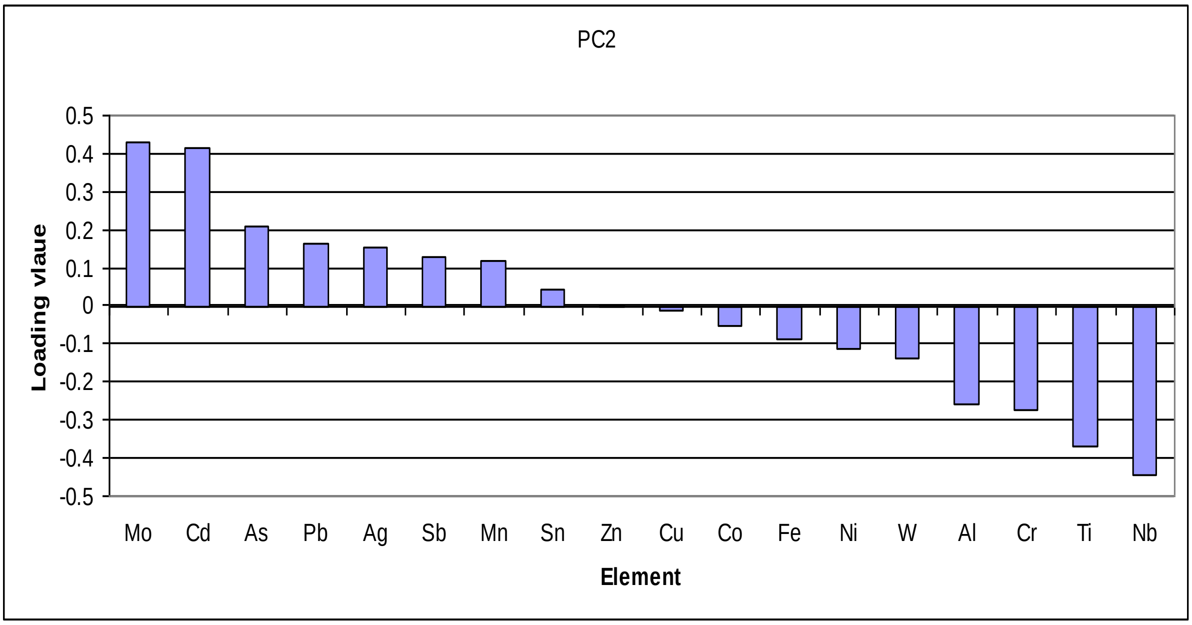

Figure 16. Element loadings for Principal Component 2, metallic and pathfinder elements on till in Tellus Border area.

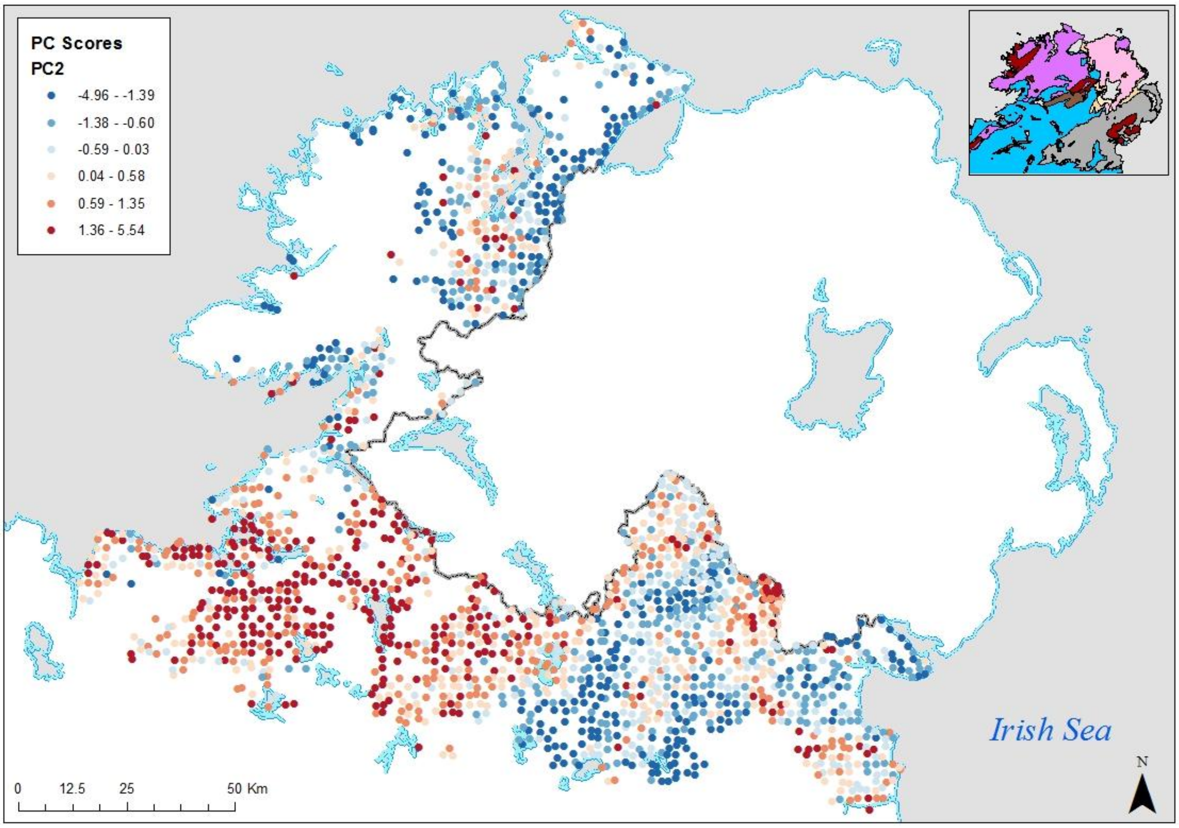

Figure 17. Principal Component 2 Score distribution for metallic and associated elements in the Tellus Border on areas of till superficial geology. Insert shows simplified bedrock geology - see Fig.1 for key.

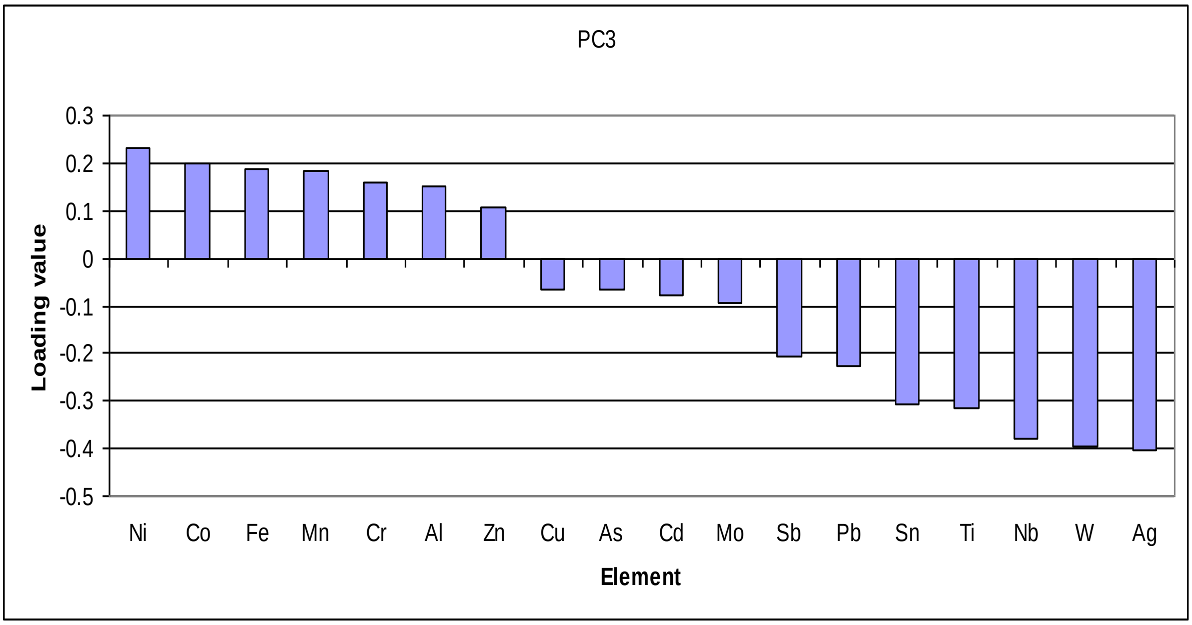

Figure 18. Element loadings for Principal Component 3, metallic and pathfinder elements on till in Tellus Border area.

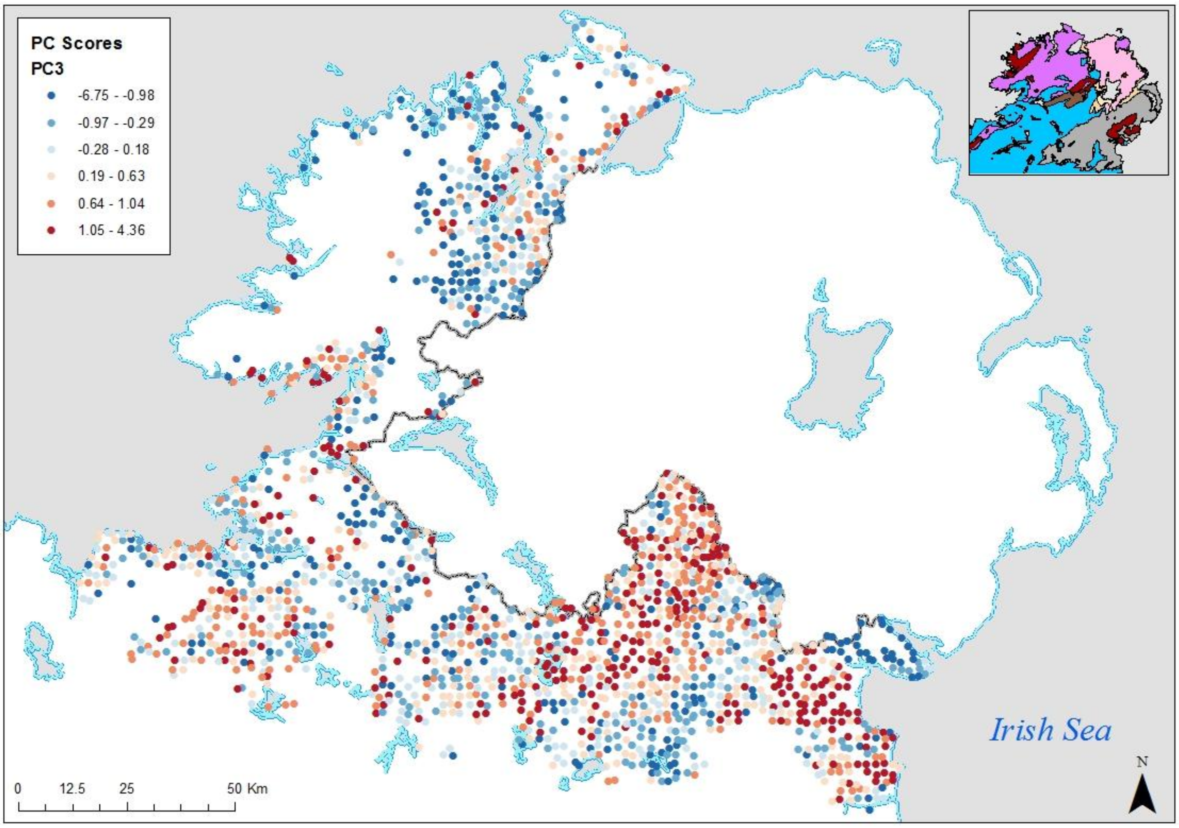

Figure 19. Principal Component 3 Score distribution for metallic and associated elements in the Tellus Border on areas of till superficial geology. Insert shows simplified bedrock geology - see Fig.1 for key.

3.1.2.1 Interpretation of Tellus Border regional PCA results for metals, semimetals and pathfinder elements

Score distribution for these elements is closely related to occurrence in local bedrock, with no compelling evidence of glacial dispersal from bedrock ore sources. The PC1 high loading element group Co, Ni, Fe is consistent with the volcanogenic material in the greywacke and shale in the south east of the survey area, but in combination with Zn it is indicative of mineralisation. East Monaghan has a concentration of almost exclusively highest scores to the southeast of Monaghan town and extending south southwest into Cavan and southeast into Louth. The latter score distribution is consistent across the boundary between the greywackes and shales and limestones so may indicate mineralisation or dispersal to the southeast. The high scores in Monaghan coincide with highly faulted bedrock and known sulphide mineralisation so the score distribution is again likely closely related to local bedrock. High scores around the Carlingford igneous centre also relate to known sulphide presence. In south Donegal, a small group of high scores also correlates well with known occurrences of lead, copper and sphalerite and in north Donegal high scores are found close to sites where gold has been detected. Low scores associated with the low loading element group Ag, Cd, Mo, Ti and W are found over the majority of the area beyond the Down-Longford Terrane. This group is strongly suggestive of sulphide mineralisation, although concentrations of low scores do not coincide with recorded occurrences but may reflect organic sulphides in shales and pelites.

The PC2 high loading element group Mo, Cd, As, Pb and Ag are indicative of sulphide mineralisation and a group of high scores are observed around and to the northeast of Castleblaney in east Monaghan, matching the area identified by high scores in PC1. The mid-high scores continue south into Louth across the greywacke and shale and limestone boundary and also to the southwest into Cavan. A small group of high scores in south Donegal also correlates well with known occurrences of lead, copper and sphalerite and there are high scores also recorded in central Donegal, south of Lough Swilly. Over the Carboniferous strata in the south of the study area, high scores are interpreted as reflecting organic sulphides in shales. The lowest loading elements would suggest metamorphosed sandy rocks and low scores are found concentrated on such bedrock in the southeast (greywacke) and northwest (quartzites and psammites) of the study area.

In PC3 the low loading element group Sn, Ti, Nb and Ag indicates mineralisation and low scores are found concentrated around the Carlingford igneous centre, east Monaghan and south-east Cavan. Sulphide deposits are known in Monaghan in this area and a copper anomaly has been recorded for the area of Cavan that has low scores. A low scoring area is also found to the northeast of the Proterozoic rocks in north Leitrim where gold and base metals have been historically recorded. Low score groups in Donegal correlate well with known mineralised areas and a small group is observed southwest of the Barnesmore Granite. High loading elements Ni, Co, Fe, Mn and Cr suggest basic igneous material but are found in the south-east on the greywacke and shale so likely reflect the volcanic material in this bedrock and in other areas the element group appears strongly associated with sand rich material. In central Sligo the distribution of high scores onto limestone dominated areas may indicate glacial dispersal of sandstones from the south.

3.2 Testing till provenance against ice flow directions indicated by bedform morphology

The study area has a high density of subglacial bedforms and recent work on drumlin and ribbed moraine geomorphology (Greenwood and Clark 2008; 2009a,b) has produced a compilation of distinct flow sets that record the former ice flow pathways of the last Irish Ice Sheet in this region. Four different kinds of flow set are present within the study area, these are (1) isochronous (sustained ice flow in single direction) (2) time transgressive (fluctuating flow line) (3) time transgressive (retreating margin) and (4) unknown, where either the number or size of drumlins in an area is too small to determine a glaciological context (see Figure 3). There are eight isochronous, six time transgressive (fluctuating flow line), two time transgressive (retreating margin) and three unknown flow sets either wholly within the study area or with a cross border aspect (see Figure 4). These provide a good opportunity to investigate glacial sediment provenance in a range of glaciological contexts and the following section presents the results from analysis conducted on each flow set type within the study area. Each flow set was given a designated reference number (e.g. LIN fs35) by Greenwood and Clark, 2009a, b and we use the same nomenclature in this report to aid cross referencing with the original publications.

As in the previous section, the figures show the PC score distribution for principal components with eigenvalues >1. The scores are represented by a divergent colour scheme with orange to red representing increasingly positive scores, and light to dark blue increasingly negative scores. Each dot represents a single sample point and individual colours equate to a score range for each PC, but as the data is not normally distributed the score ranges are not equal number increments across the maps.

3.2.1 Isochronous: lineation flow sets 35 and 37

An area of south Donegal surrounding Donegal Bay contains two isochronous flow sets that cross cut one another (LIN fs35 and LIN fs37) (see Figs. 3, 4 and 20). Based on superimposition of landforms, LIN fs37 is interpreted as being the older and LIN fs35 the younger event (Greenwood and Clark, 2009b) with general ice flow direction to the southwest (LIN fs37) and west-southwest (LIN fs35).

The geology of the area of the flow sets is dominated by Carboniferous strata that can be broadly split into two areas, with clastic lithologies to the northwest and limestones to the southeast (Fig. 21). Proterozoic psammite and pelite outcrop in the northwest and southeast margins of the flow set area and the Barnesmore Granite is situated immediately to the north-east.

3.2.1.2 Principal component scores for samples within LIN fs35 and LIN fs37

A total of 76 sample points on till fall within the overlapping flow set areas and PCA returned seven significant PCs (Fig.21) which explain 82.6% of the variance. NB only the most illustrative PCs are presented here. The remainder of the PCs can be found on the CD-ROM of additional material that accompanies this report.

PC1 accounts for 40.1% of the variance and has highest loading (>0.23) elements Sc, Co, Ni, Fe_2O_3, Al_2O_3, Zr, Zn and Ce (Fig.22). High scores associated with these elements are observed in the central, west and southeast of the sample area (Fig. 23). The lowest loading elements ($\leq$0.15) are CaO, Hf, Sr, Ga, Se, Nb, MgO with TiO_2 the only negative loading element, and low scores are found in the east and north.

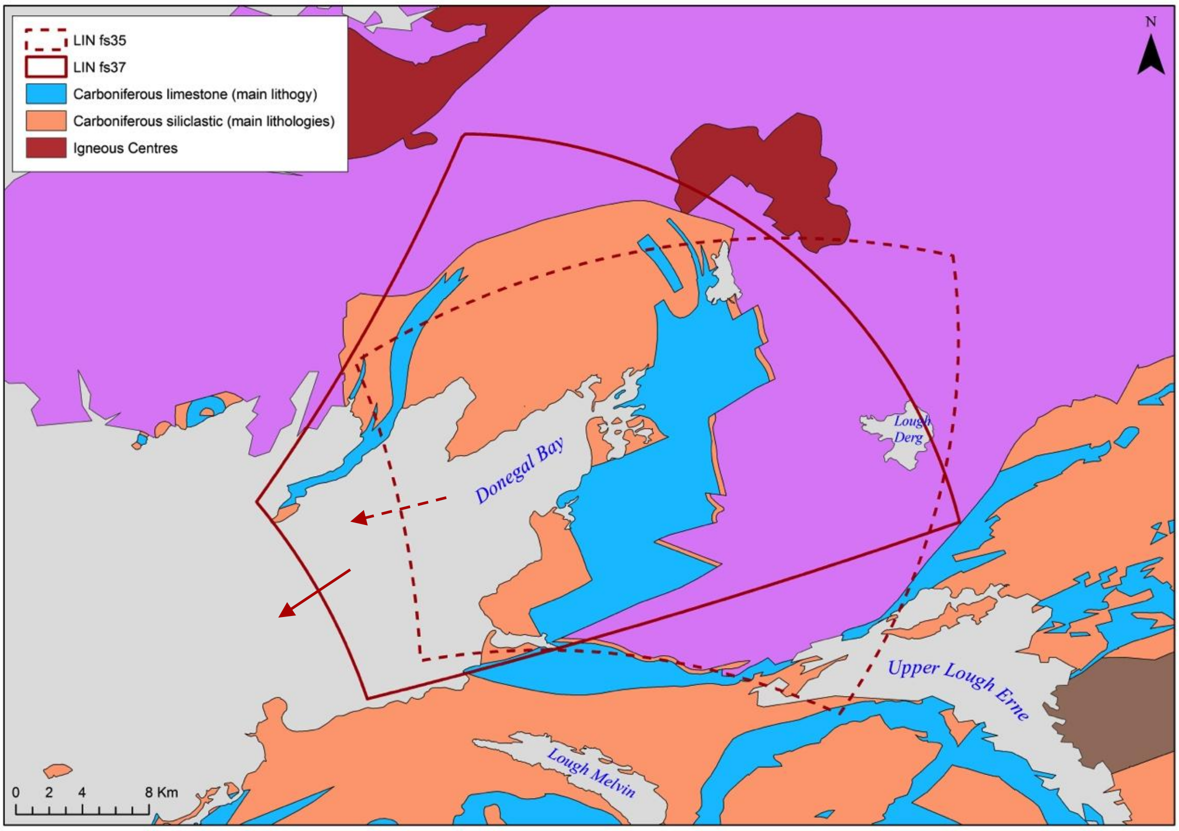

Figure 20. Detailed geology of south Donegal with two isochronous flow set outlines and their flow directions.

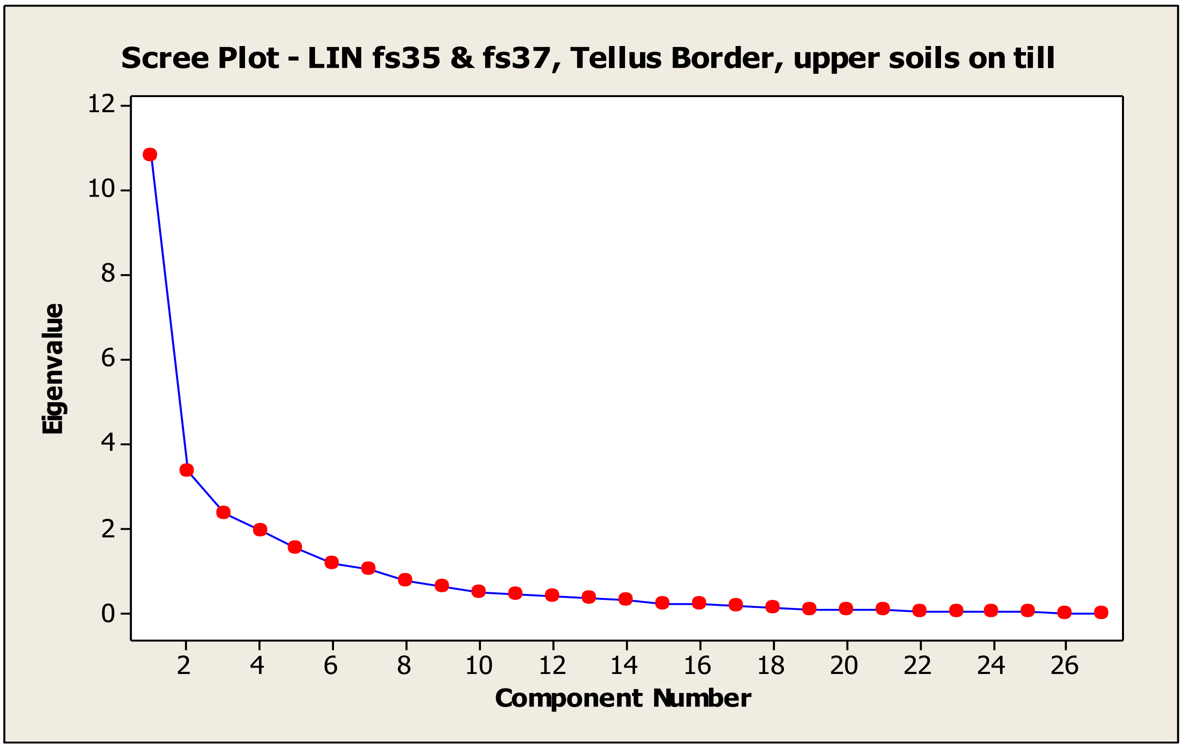

Figure 21. Scree plot of Principle Component eigenvalues for upper soil samples taken on areas of till superficial geology LIN fs35 and LIN fs37. In this study the first seven PCs have eigenvalues >1 so are the most significant for the data.

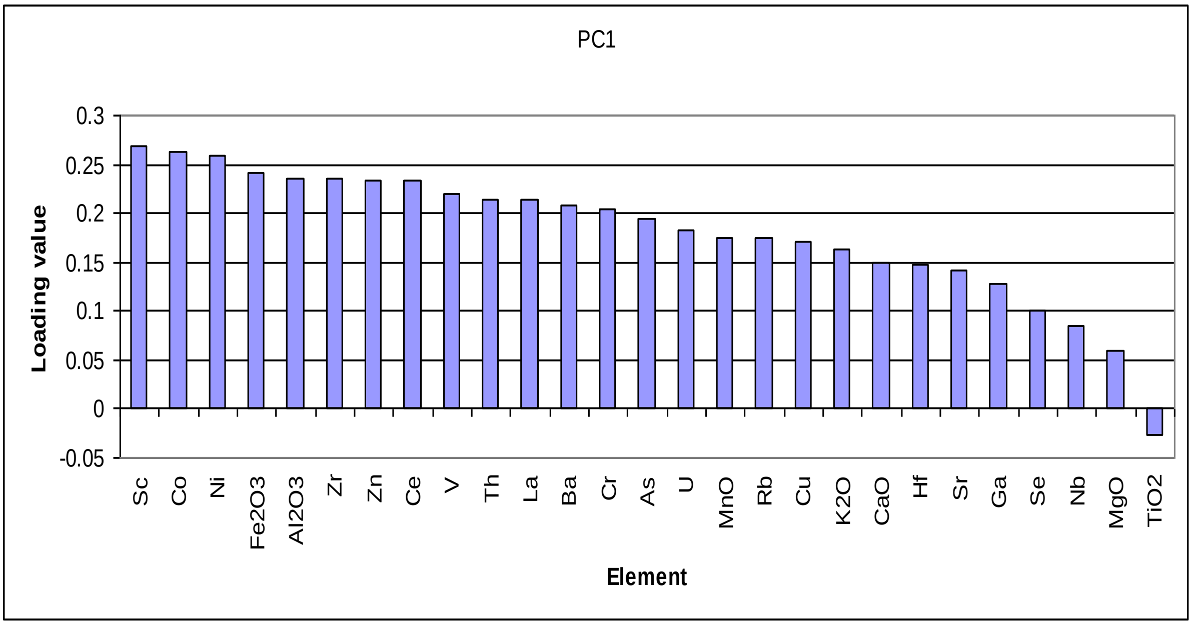

Figure 22. Element loadings for Principal Component 1, LIN fs35 and LIN fs37 sample area.

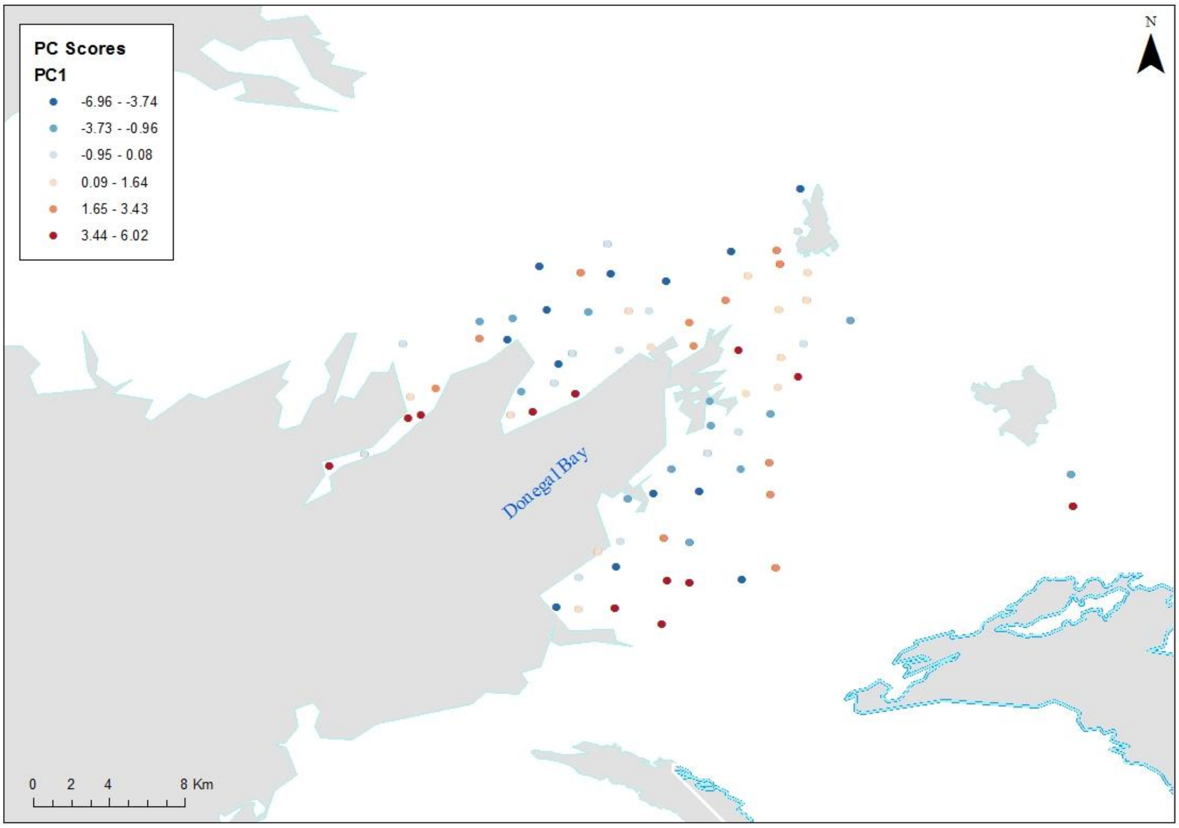

Figure 23. Principal Component 1 score distribution for LIN fs35 and LIN fs37 sample area.

PC2 (12.4% of variance) has highest loading (>0.2) elements Se, CaO, U, As and MnO (Fig. 24) and high scores associated with these elements are found concentrated in the south of the sample area in close association with limestone (Fig. 25). The lowest loading elements (<-0.2) are Al_2O_3, Rb, K_2O and Ga and low scores are concentrated in the north of the sample area in association with clastic sedimentary rocks.

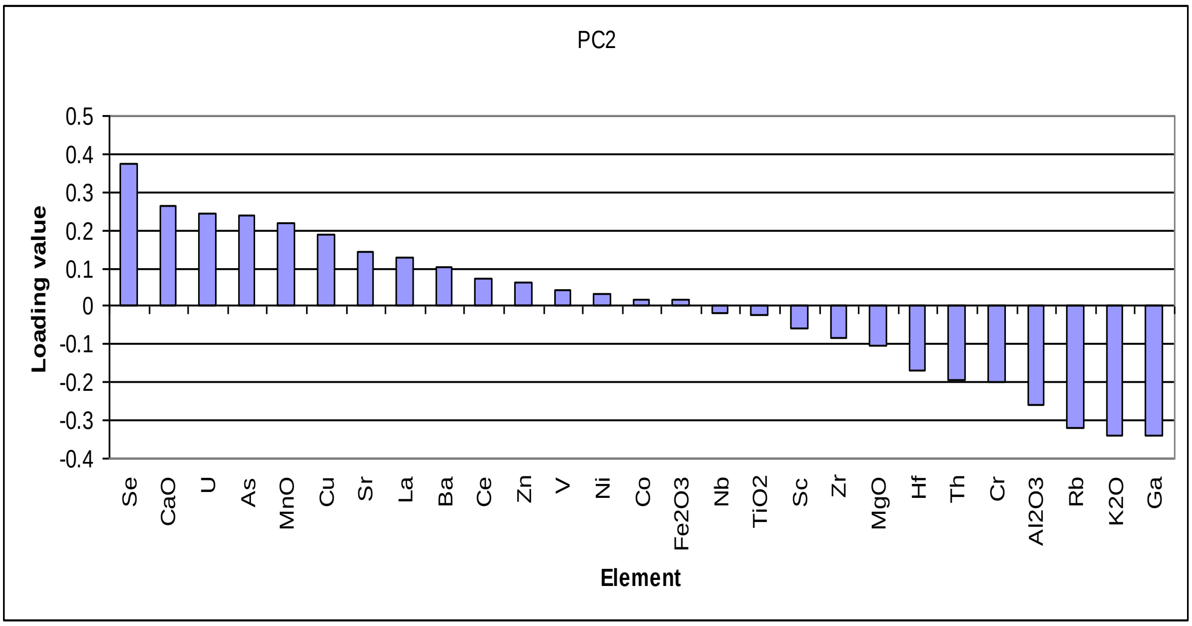

Figure 24. Element loadings for Principal Component 2, LIN fs35 and LIN fs37 sample area.

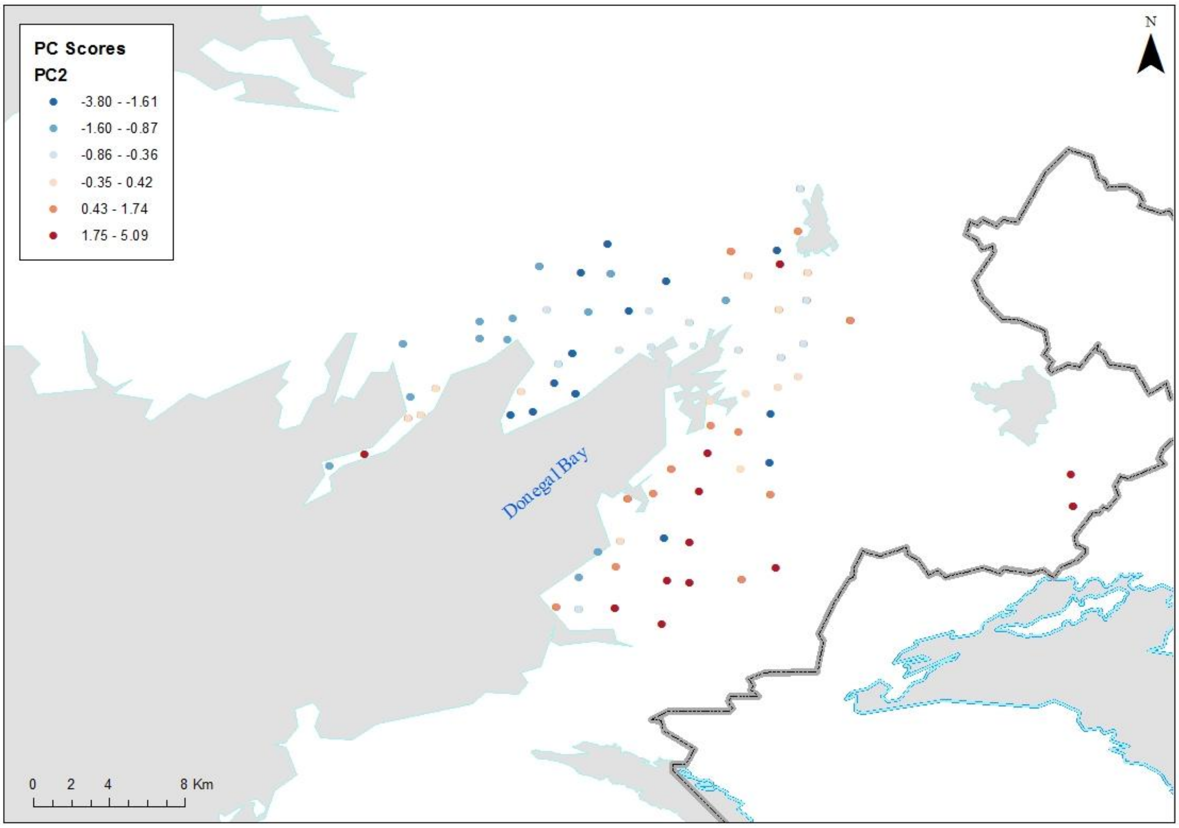

Figure 25. Principal Component 2 score distribution for LIN fs35 and LIN fs37 sample area.

PC3 accounts for 8.8% of the variance in the data and the highest loading elements (>0.2) are Nb, La, U, Ce and Ba (Fig. 26). High scores are observed concentrated in the north of the sample area (Fig. 27). The lowest loading elements (<-0.2) are Ni, Co, Fe_2O_3, MgO and MnO with low scores recorded particularly in the south of the sample area.

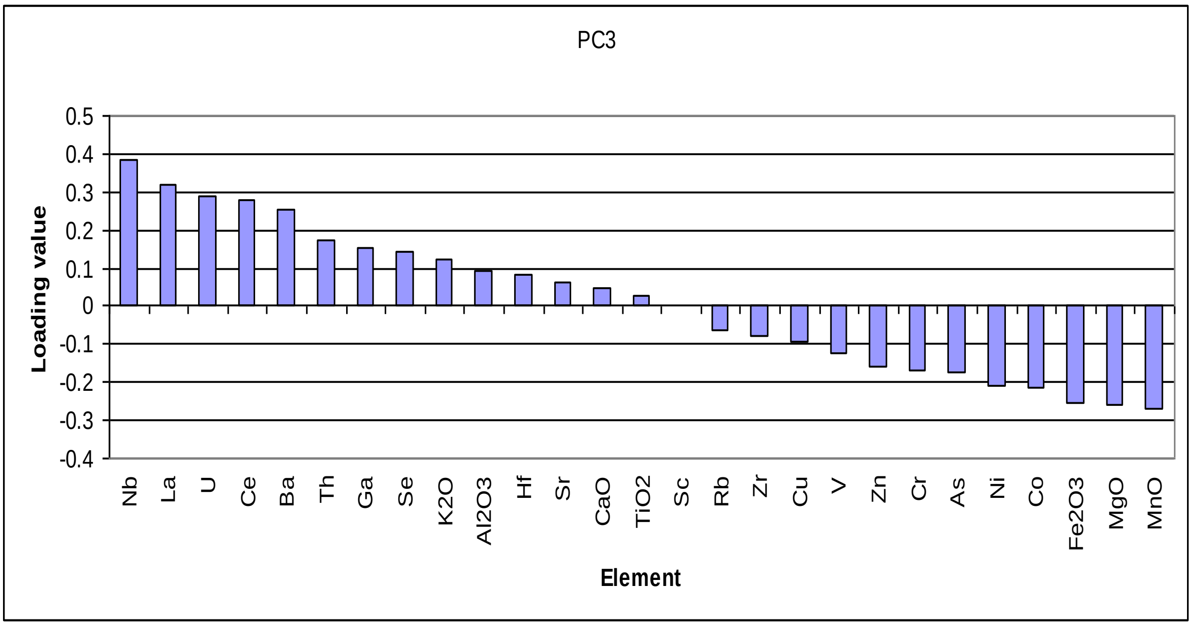

Figure 26. Element loadings for Principal Component 3, LIN fs35 and LIN fs37 sample area.

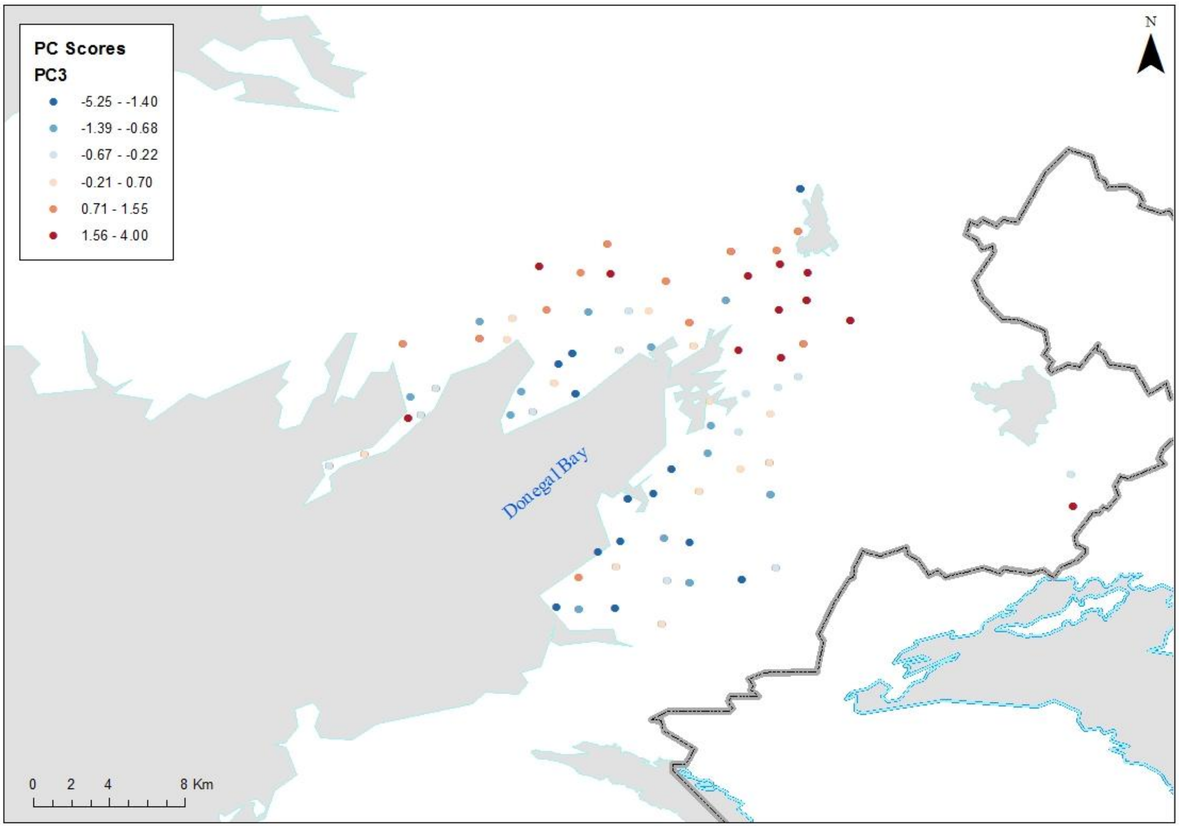

Figure 27. Principal Component 3 score distribution for LIN fs35 and LIN fs37 sample area.

PC4 accounts for 7.3% of the variance in the data and the highest loading elements (>0.2) are Sr, CaO, Hf and Zr (Fig. 28). High scores are observed concentrated in the centre of the sample area (Fig. 29). The lowest loading elements (<-0.2) are Ce, V, Ga, La, Cu and MnO with low scores recorded around the fringes of the sample area, particularly on the east side.

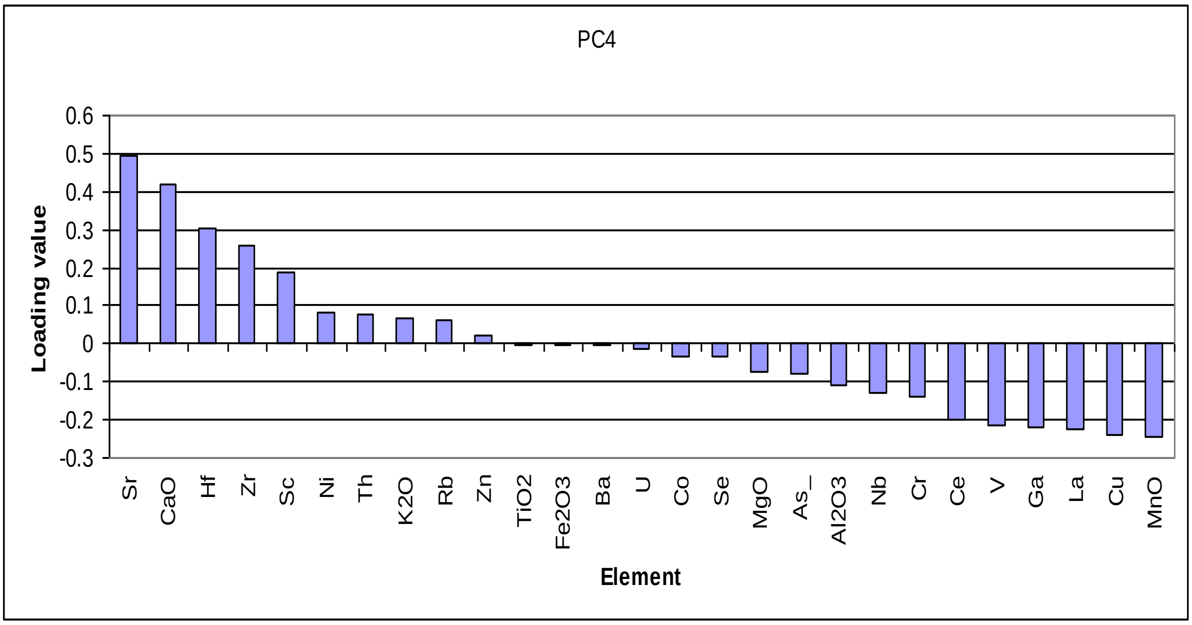

Figure 28. Element loadings for Principal Component 4, LIN fs35 and LIN fs37 sample area.

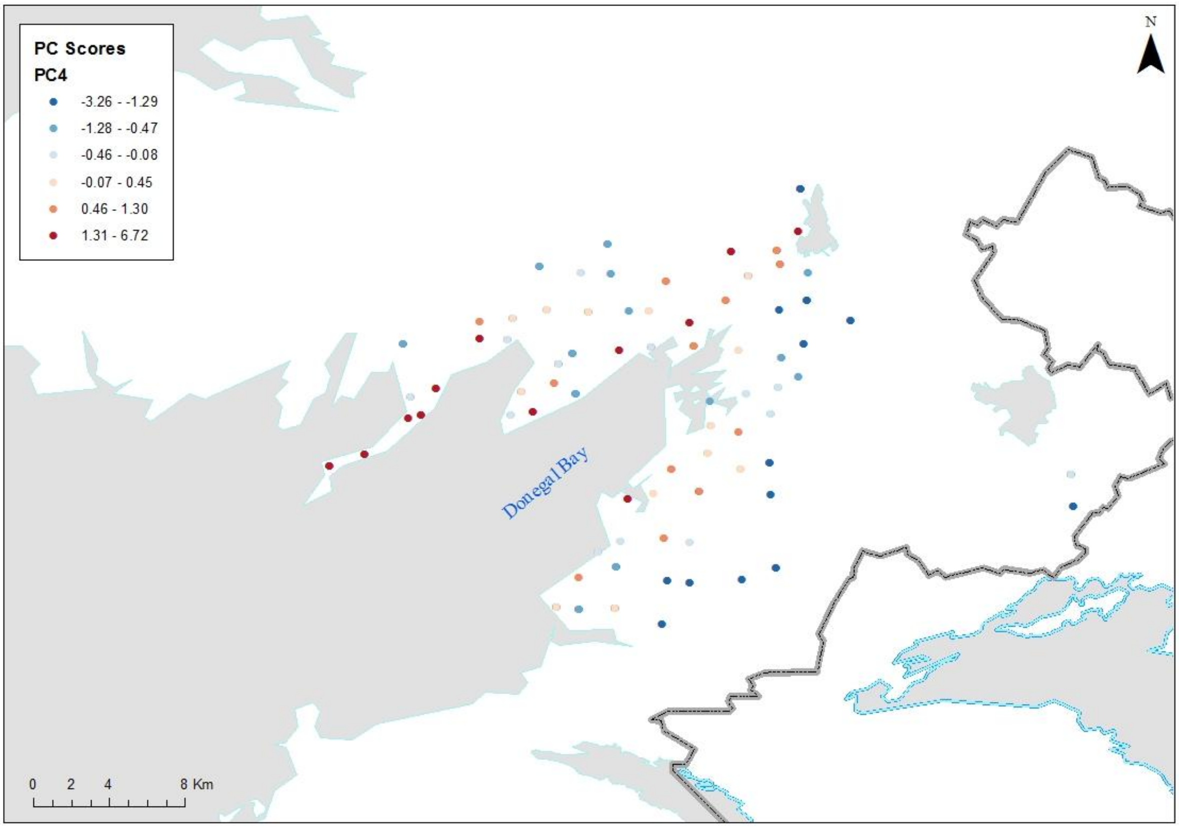

Figure 29. Principal Component 4 score distribution for LIN fs35 and LIN fs37 sample area.

3.2.1.3 Interpretation of PCA results for LIN fs35/37

The large high loading element group Sc, Co, Ni, Fe_2O_3, Al_2O_3, Zr, Zn and Ce in PC1 indicate clay and sand minerals and the distribution of high scores where found on limestone suggests glacial transport of approximately 2-8km to the west and south-west of material from the surrounding Proterozoic meta-sediments. The low loading of CaO, Sr and MgO correlate well with the scores found on limestone, and low scores area also found over the siliclastic bedrock to the north-west indicating glacial transport of material generally to the west, though limestones are also interbedded with the siliclastic sediments. The elements Sr, TiO_2, Ga, Se and Nb suggest siliclastic material and are also low loading, which indicates mixing of siliclastic and carbonate material in the low scoring areas, either directly from the bedrock or from material transported from the Proterozoic meta-sediments.

In PC2 the high loading elements are closely associated with limestone in the south-east and CaO returns the second highest loading. The remaining high loading element group Se, U, As and MnO is not typical of limestone and is more suggestive of mineralisation, and the high scores do appear close to reported occurrences of sulphide metals in the south of the sample area. The low loading element group Al_2O_3, Rb, K_2O and Ga is indicative of clay minerals and the low scores plot in close association with the shales in the north-west of the sample area. A linear east-west trending group of the mid loading element group Ce, Zn, V, Ni, Co, Fe_2O_3, Nb, TiO_2 and Sc occurs in the centre of the sample area. These elements are suggestive of clay minerals, and the elements Ce, Nb and TiO_2 would indicate a metamorphic source, and therefore glacial transport from the Proterozoic sediments to the east.

The high loading elements Nb, U and Ce in PC3 suggest a metamorphic sediment or felsic igneous mineralogy so indicate glacial transport either from the northeast or east over the sample area. In combination with the high loading of La and Ba, transport from the northeast is favoured as the Barnesmore Granite is situated immediately to the northeast of the sample area. Transport distance is therefore in the region of 12km (minimum) to the southwest towards Donegal Bay. The low loading element group Ni, Co, Fe_2O_3, MgO and MnO here indicate clay minerals and as low scores are found mainly on the limestone in the southeast of the sample area, it likely indicates glacial transport to the west from the Proterozoic meta-sediments. Sr and CaO are mid loading and mid scores are found on the limestone areas also.

The highest loading elements Sr and CaO in PC4 indicate limestones and high scores are recorded on limestones in the west and east of the sample area. However, the dominantly siliclastic sediments in the northwest also return high scores suggesting glacial transport of carbonaceous material to the west (approximately 1-6 km). The high loading of Hf and Zr also suggests sandy material, so the high scores on the dominantly siliclastic bedrock may indicate mixing of silicic and carbonaceous material in this area. The low loading element group Ce, V, Ga, La, Cu and MnO indicate clay minerals and the lowest scores are found on limestones on the east side of the sample area, suggesting glacial transport of approximately 5 km of pelitic material to the west from the Proterozoic meta-sediments.

3.2.2 Time transgressive, flowline fluctuations: lineation flow set 9

LIN fs9 is situated in the south-eastern area of the north of Ireland and includes southeast Fermanagh most of county Armagh and all county Down in Northern Ireland and most of Monaghan, all of Louth, most of Cavan and the south-eastern end of Leitrim in the Republic of Ireland, so it has a significant cross border aspect. Therefore both Tellus Border and Tellus samples have been used in the following analysis. The flow set is time transgressive and the general flow direction as interpreted from the subglacial bedform morphology indicates ice flow to the southeast towards the Irish Sea Basin.

The geology can be split into two main divisions; the Lower Palaeozoic (Ordovician-Silurian) turbidite (greywacke, shale and minor igneous intrusions) sequences of the Down-Longford Terrane and the Upper Palaeozoic (Carboniferous) mixed sediments that include limestone as a major or minor feature (Fig. 30). The turbidites dominate the flow set area, with the Carboniferous strata found in the north-western sections. The Newry, Mournes and Carlingford igneous centres are significant features in the southeast of the sample area, and smaller igneous bodies are present in north county Down, south Louth and in southeast Cavan.

3.2.2.1 Principal component scores for samples within LIN fs9

A total of 2416 sample points on till fall within the flow set and is the largest sub-sampled region within the survey area. PCA returned five significant PCs (Fig. 31), which combined, explain 77.1% of the variance. NB only the most illustrative PCs are presented in this report. The remainder of the PCs can be found on the CD-ROM of additional material that accompanies this report.

PC1 accounts for 42.3% of the variance in the data and has highest loading (>0.25) elements Fe_2O_3, Al_2O_3, Co, Ni, Cr and Ga (Fig. 32). High scores are observed in association with basalt and the turbidite sequences in counties Down, Armagh, Monaghan and Louth (Fig. 33). Lowest loading elements (<0.14) are Th, As, CaO, Sr, Nb with U and Se returning negative loading and associated low scores are recorded for the east coast of the Ards Peninsula, the Newry, Mournes and Carlingford igneous centres and the Carboniferous mixed sedimentary sequences to the west/south-west of Lough Neagh. Mid scores are observed to the northwest of the Newry igneous centre.

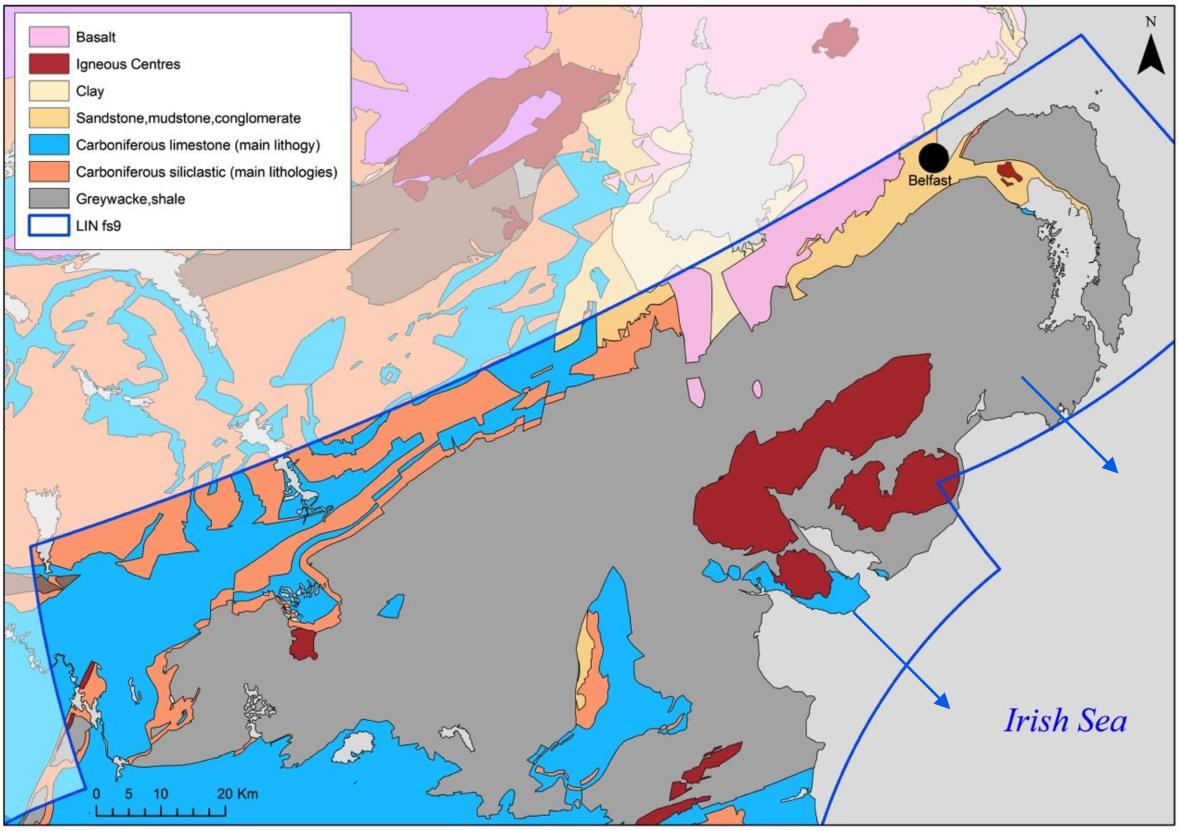

Figure 30. Simplified geology in the southeast of north Ireland, with time transgressive (fluctuating flow line) LIN fs9.

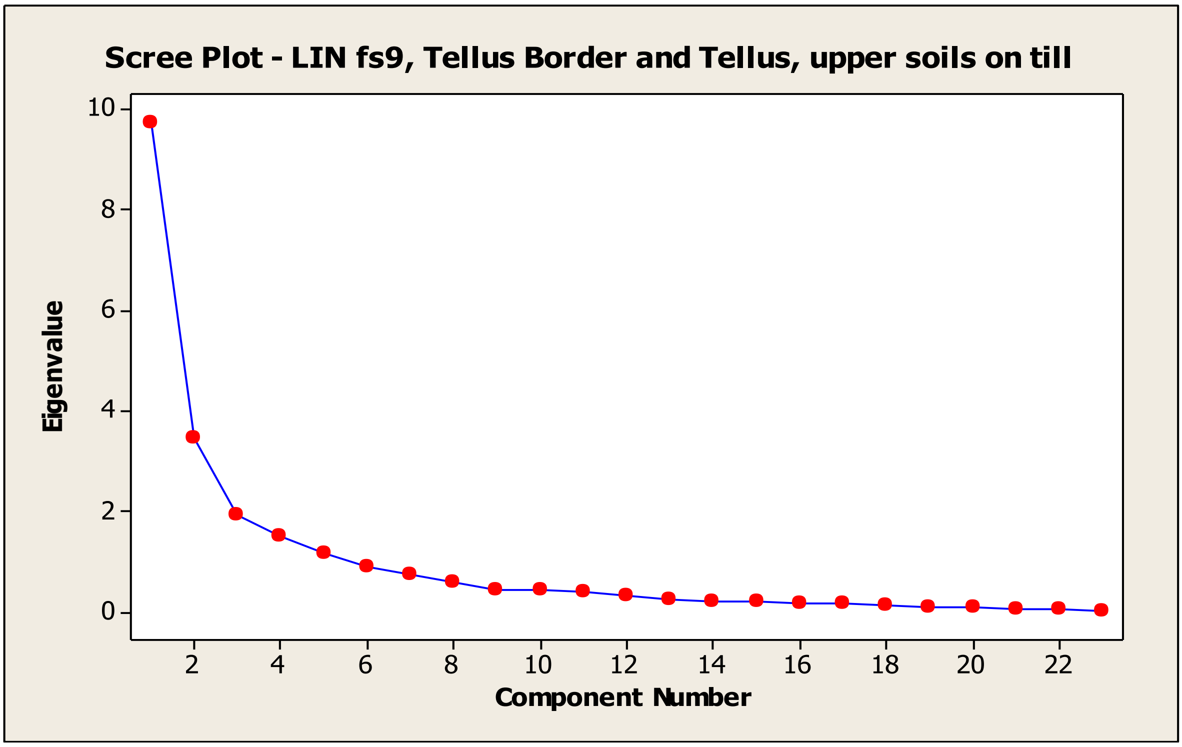

Figure 31. Scree plot of Principle Component eigenvalues for upper soil samples taken on areas of till superficial geology LIN fs9. In this study the first five PCs have eigenvalues >1 so are the most significant for the data.

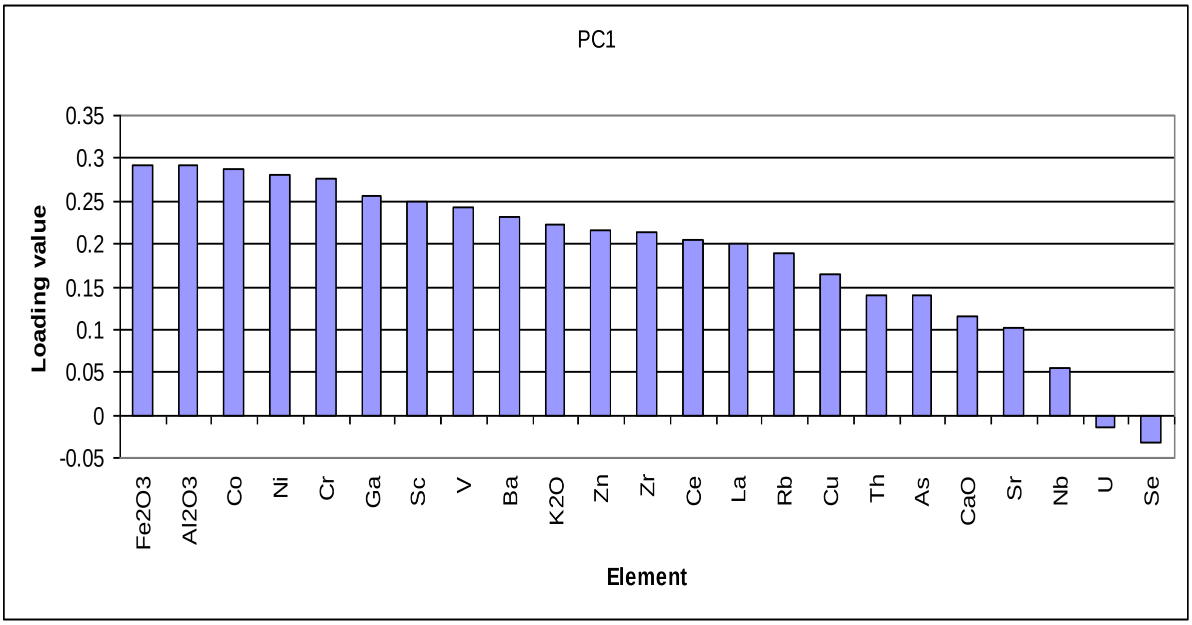

Figure 32. Element loadings for Principal Component 1, LIN fs9 sample area.

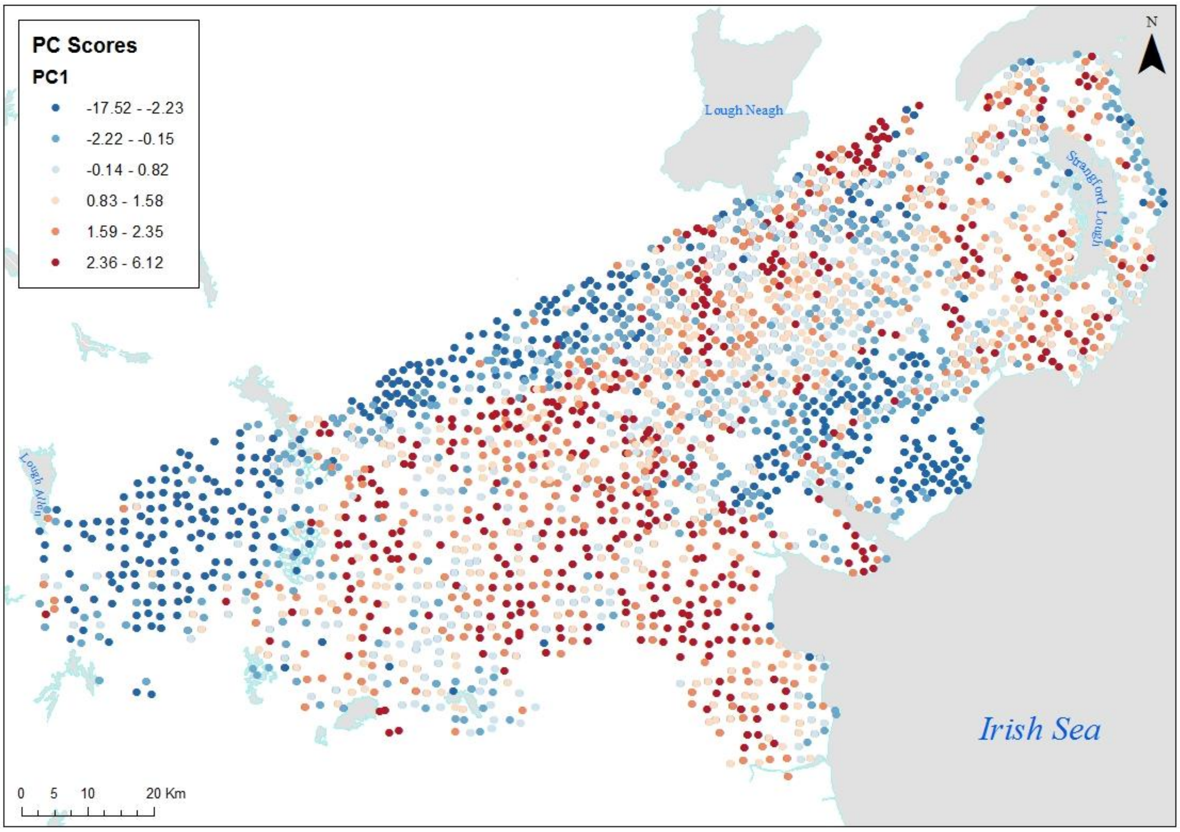

Figure 33. Principal Component 1 score distribution for LIN fs9 sample area.

PC2 (15.0%) of variance has highest loading (>0.15) elements Sr, V, CaO, Sc, Ni and Cr (Fig. 34) with high scores associated with these elements found along the north-west margin of the sample area, and between Lough Neagh and the Newry igneous centre (Fig.35). A line of mid-high scores is observed extending to the southwest from county Armagh, through Monaghan and into Cavan. The occurrence and trend of this feature fits closely with the outcrop of the Gilnahirk/Red Island formation. Mid scores are recorded along the east coast of the Ards Peninsula, central and east Louth and in south Cavan. The lowest loading elements (≤-0.23) are U, As, Rb, Th, Ce and La with associated low scores in south county Down including the Mournes and extending southwest from south Armagh through to Cavan.

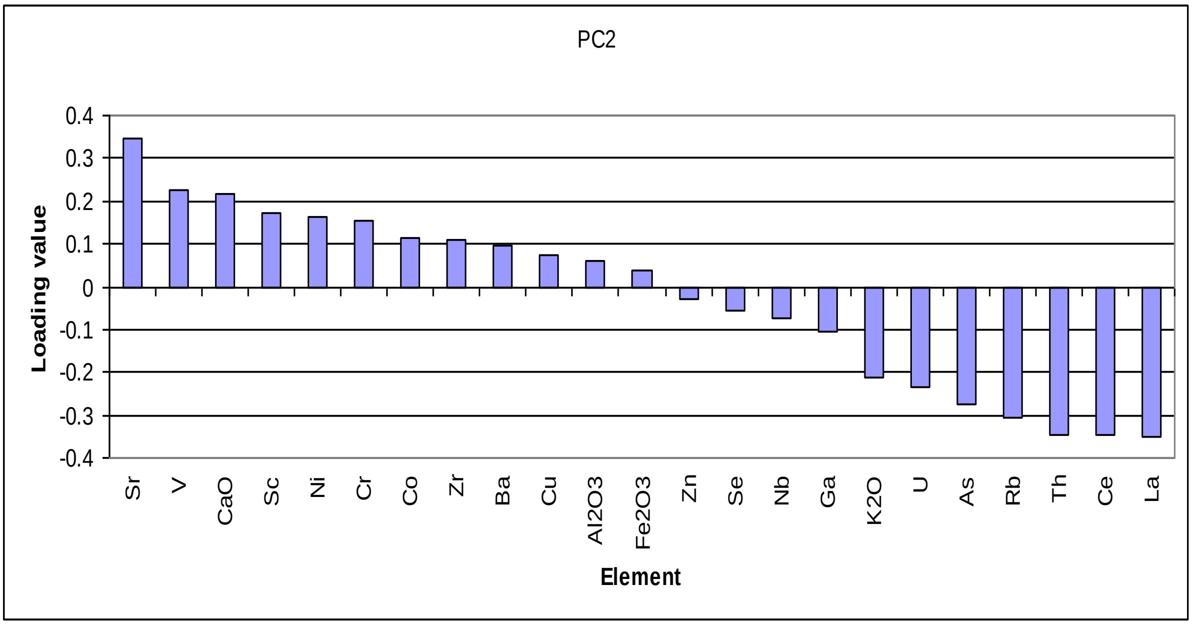

Figure 34. Element loadings for Principal Component 2, LIN fs9 sample area.

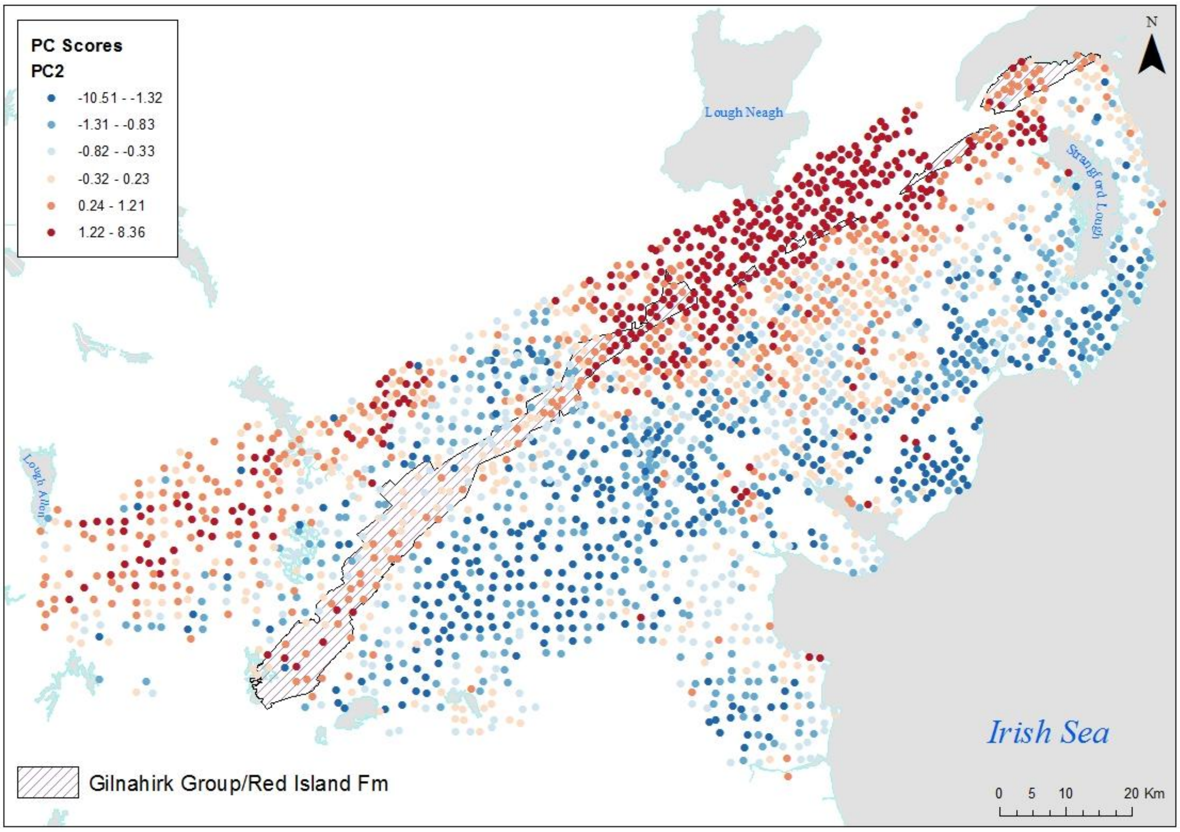

Figure 35. Principal Component 2 score distribution for LIN fs9 sample area. The relationship between the outcrop of the Gilnahirk Group/Red Island Formation and the extension of mid-high scores can be clearly seen .

PC4 accounts for 6.5% of the variance in the data and the highest loading elements (>0.14) are Ba, CaO, As, Ce and Sr (Fig. 36). High scores associated with these elements are observed in the north of the sample area and in the southern section of county Louth (Fig. 37). Mid to high scores are recorded in east county Down and the Ards Peninsula. The lowest loading elements (<-0.13) are U, Cr, Al_2O_3, V, Ga and Nb with low scores concentrated in south county Down and north Louth in close association with the Newry, Mournes and Carlingford igneous centres. Low scores are also recorded in central Down between the Newry igneous complex and Lough Neagh in north Down and in south Cavan.

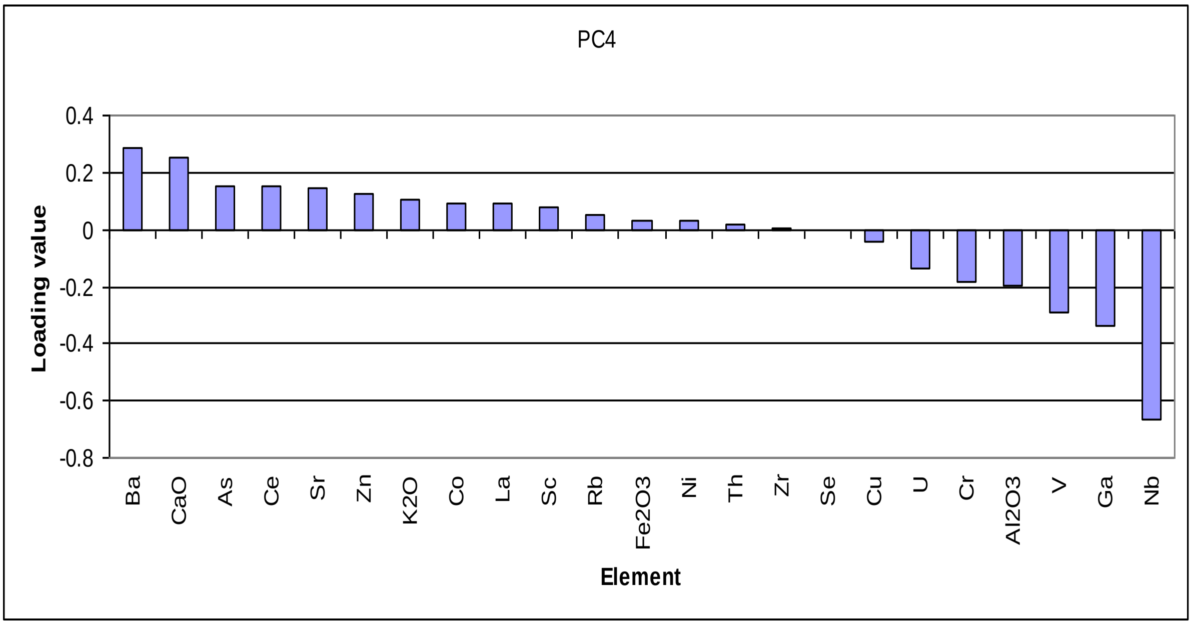

Figure 36. Element loadings for Principal Component 4, LIN fs9 sample area.

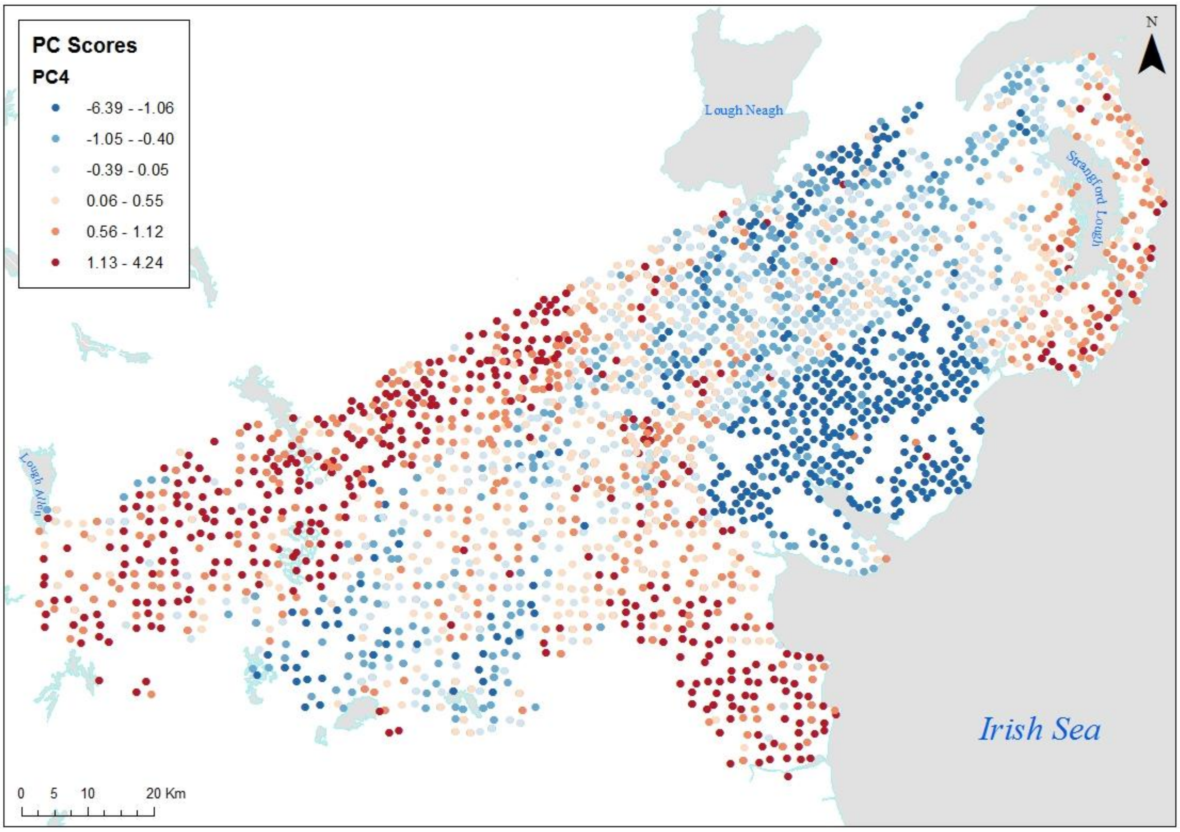

Figure 37. Principal Component 4 score distribution for LIN fs9 sample area.

3.2.2.2 Interpretation of PCA results for LIN fs9

High loading of Fe_2O_3, Al_2O_3, Co, Ni, Cr and Ga in PC1 is indicative of mud rich or basic igneous material, with high scores conforming strongly to outcrop of the greywacke, shale and basalt in the study area. High scores are also recorded to the southeast of the Carlingford igneous centre on limestone bedrock, indicating transport of greywacke and shale over this area. The low loading of CaO and Sr explain the association of low scores with predominantly limestone areas in the central, northern and west sections of the sample area, with the other low loading elements Th, As, Nb and U accounting for the low scores on the Newry and Mournes igneous centres. Low scores are also found between these igneous bodies and to the south of the Mournes on greywacke and shale demonstrating transport of igneous material to the southeast of up to 4km. Low scores recorded on the north-eastern edge of the sample area on the coast of the Ards Peninsula may be from off shore material transported on shore by Irish Sea Ice, or post glacial processes that have increased the CaO content of the soils for example through accumulation of shelly debris.

In PC2 once more high loading of Sr and CaO explains the high scores on limestone rich bedrock areas on the north-western region of the sample area. High loading of V, Sc, Ni and Cr indicates either basic igneous or clay rich material and there is a concentration of highest scores found in close association with basalt and the igneous outcrop (dolerite) at the north end of Strangford Lough. High scores continue beyond the basalt outcrop to the southwest onto Carboniferous strata and Lough Neagh Clay, and also to southeast over greywacke and shale and across Triassic sandstones. This indicates glacial transport of material of at least 10km from the basalt in this direction. However, high scores are also found to follow the outcrop of the Gilnahirk Group/Red Island Formation very closely when the majority of the greywacke and shale of the southeast return low scores. This means the extension of high scores to the southeast may also be related to transport of this material, giving a minimum transport distance of 4km. The high to mid scores recorded on the east coast of the Ards Peninsula may represent transport of the Gilnahirk Group to the southeast by Irish Sea ice. Low loading of Ce and La explain the low scores found over much of the greywacke and shale bedrock and U, As, Rb and Th the low scores on the Newry and Mourne igneous centres. Scores do get progressively lower to the southeast in the eastern part of the sample area and this might be due to progressive attenuation of the basalt/Gilnahirk Group content of the till in this direction.

The high loading element group Ba, CaO, As, Ce and Sr in PC4 suggests both carbonate and clay rich material and high scores correlate well with bedrock in limestone dominated and mud rich sediments. The low loading elements U, Cr, V, Ga and Nb would indicate basic rocks or shale and low scores are recorded for the Antrim basalts, though low scores are also found on the dominantly granitic Newry and Mourne igneous centres. This may be explained by the high loading Al_2O_3 which is likely to relate to feldspar in the felsic material. Low scores found between the Antrim basalt and the Newry and Mournes igneous centres may represent southeast transport of basaltic material or post glacial dispersal of granitic material north by watercourses draining to Lough Neagh. However in north County Down the low scores may represent glacial transport of basaltic material from south Antrim. The trend of low scores in Monaghan and south Cavan do not correlate with bedrock or the dominant ice flow directions, but do correlate with possible mineralisation (See section 3.2.1), so are related to local geology.

3.2.3 Time transgressive, retreating margin: lineation flow set 22

LIN fs22 is situated in central Sligo and ice flow direction as indicated from subglacial bedform interpretation is to the north and northwest (Fig. 38). The flow set area is dominated by Carboniferous limestone and siliclastic sediments with Proterozoic metamorphic rocks outcropping on the northern margin and a small area of granite is present in the north-western corner of the sample area.

3.2.3.1 Principal component scores for samples within LIN fs22

A total of 90 sample points on till fall within the flow set and PCA returned five significant PCs, which combined explain 81.9% of the variance. NB only the most illustrative PCs are presented in this report. The remainder of the PCs can be found on the CD-ROM of additional material that accompanies this report.

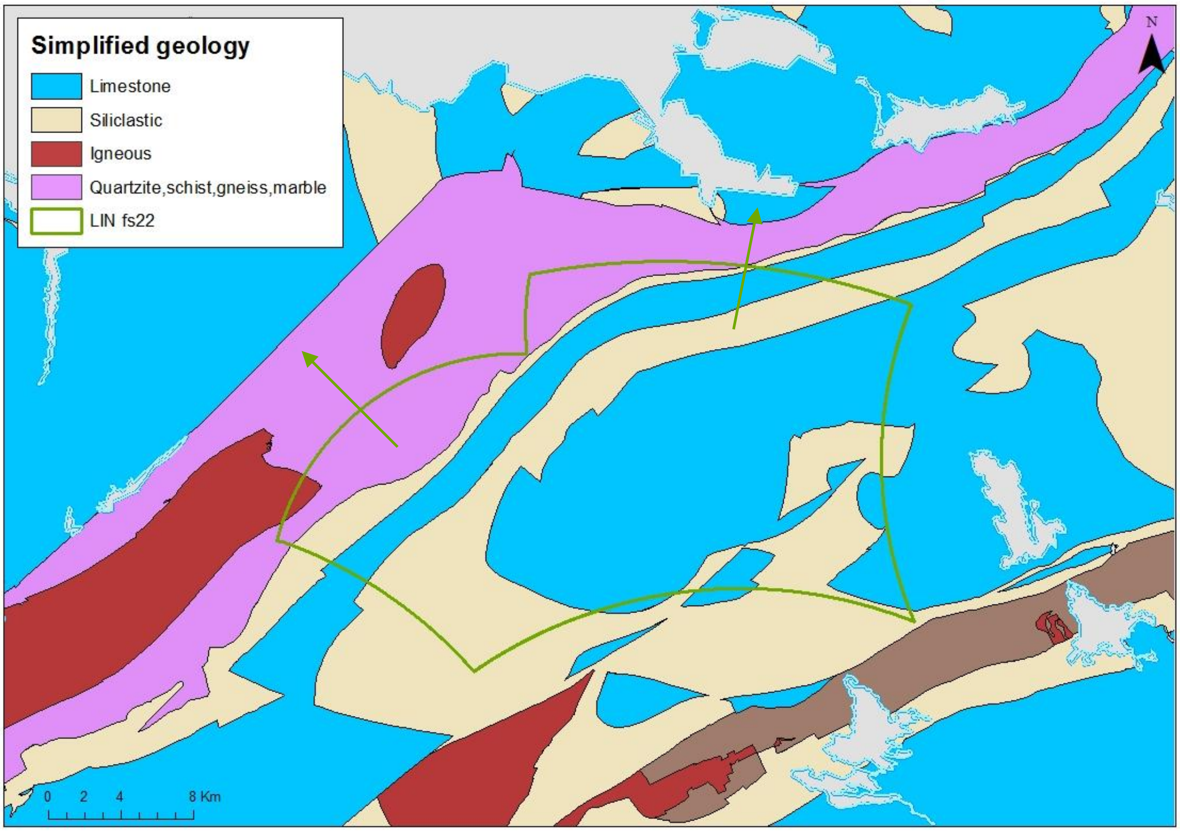

Figure 38. Simplified geology for county Sligo and surrounding area, with time transgressive (retreating margin) LIN fs22.

PC1 (54.9% of variance) has highest loading (≥ 0.24) elements Sc, Al_2O_3, Fe_2O_3, Cr and Co (Fig. 39). High scores associated with these elements are observed concentrated across the eastern side of the flow set area (Fig. 40). Lowest loading elements (< 0.10) are Sr, CaO, Nb and TiO_2 with low scores found predominantly in the western side of the sample area.

PC2 accounts for 9.3% of the variance and has highest loading (>0.2) elements Sr, CaO, Zn and U (Fig. 41) with associated high scores to the east and southeast (Fig.42). The lowest loading elements (<-0.2) are Th, Ga, Rb and K_2O and low scores are observed in the west and southwest of the sample area.

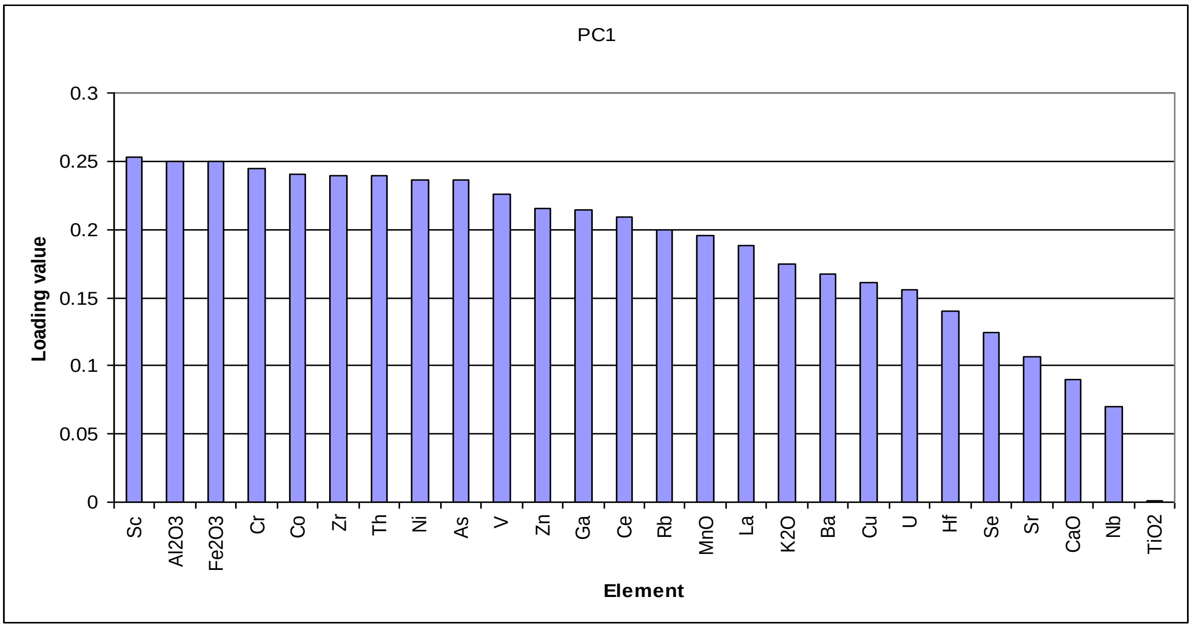

Figure 39. Element loadings for Principal Component 1, LIN fs22 sample area.

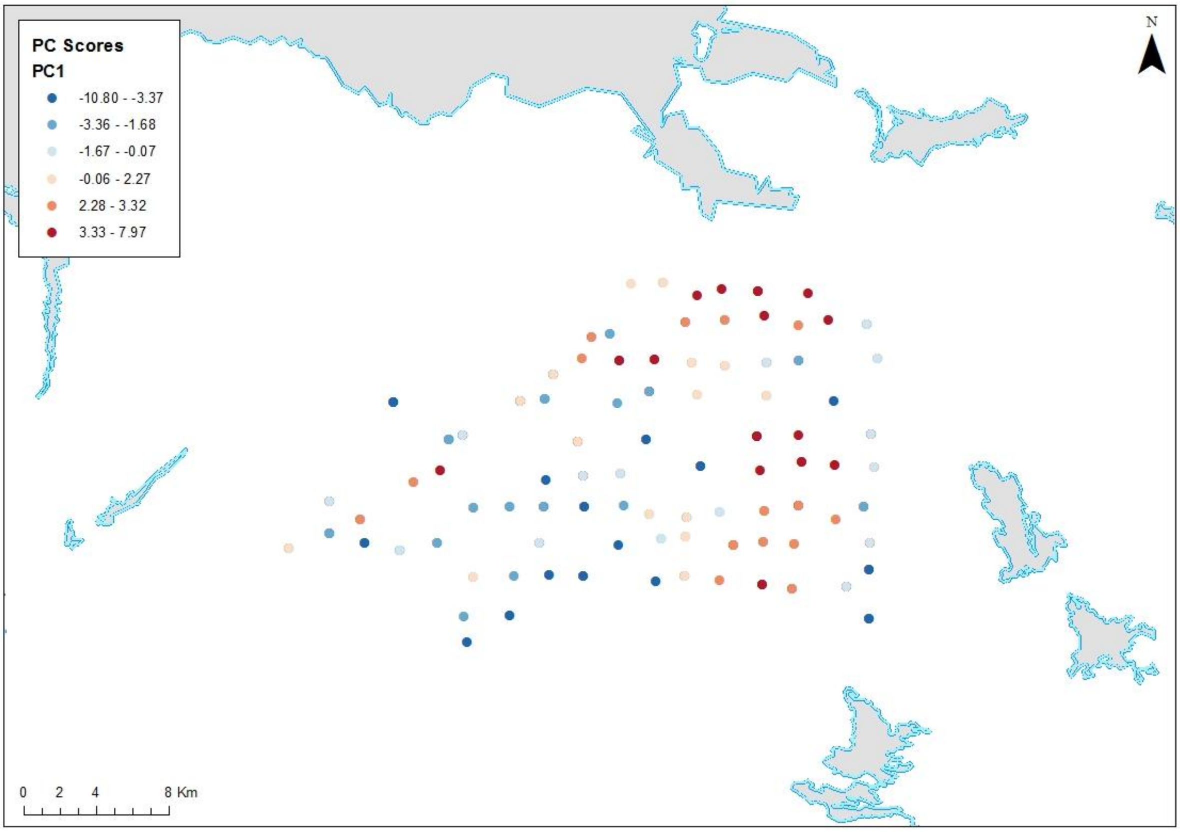

Figure 40. Principal Component 1 score distribution for LIN fs22 sample area.

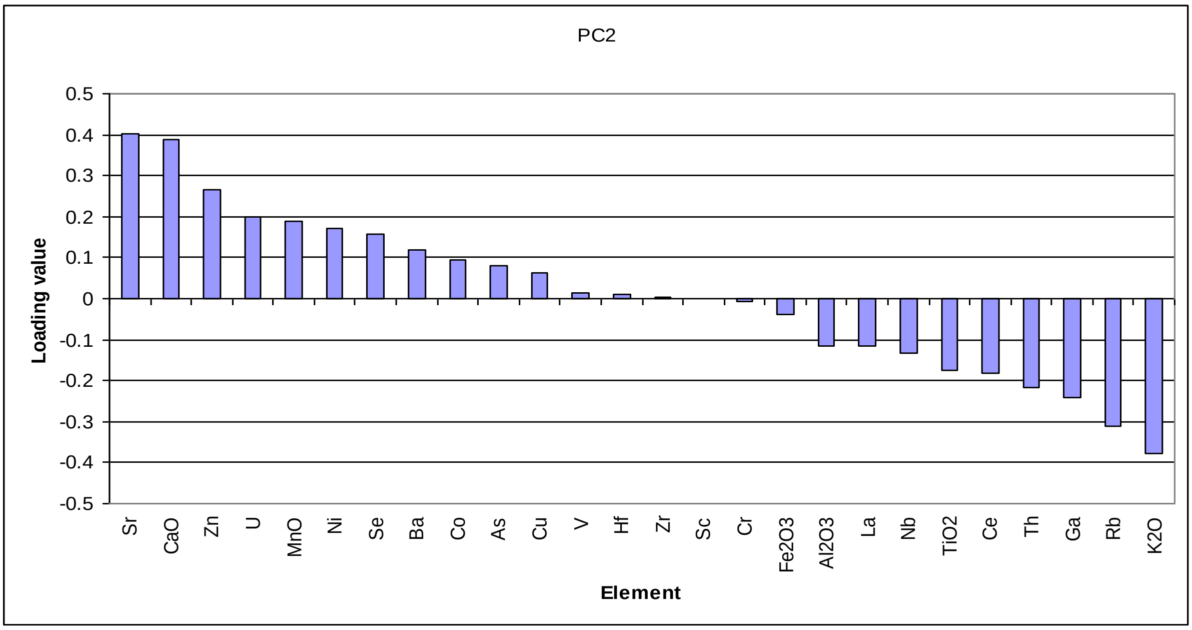

Figure 41. Element loadings for Principal Component 2, LIN fs22 sample area.

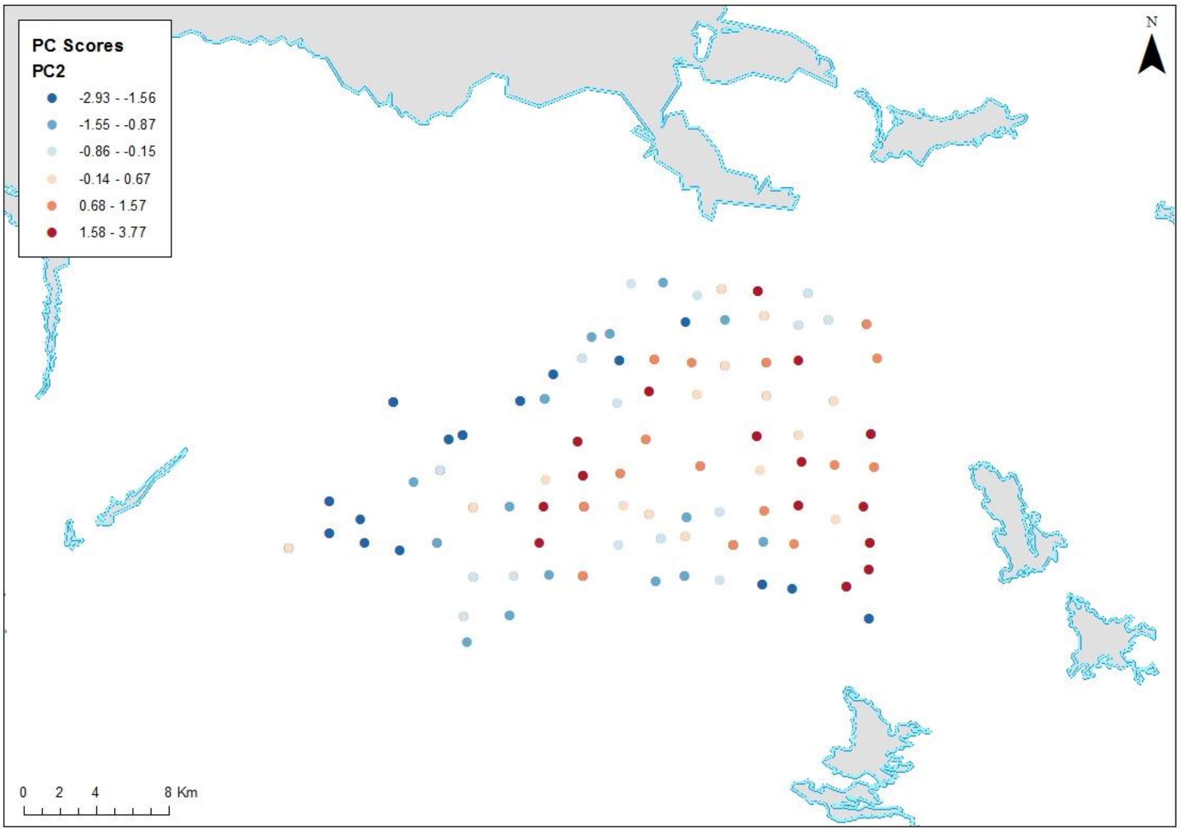

Figure 42. Principal Component 2 score distribution for LIN fs22 sample area.

3.2.3.2 Interpretation of PCA results for LIN fs22

For PC1 the high loading element group Sc, Al_2O_3, Fe_2O_3, Cr and Co suggest clay minerals and high scores are in close association with shales in the southeast, northeast and northwest of the sample area. High scores continue onto limestone in the south and northeast of the sample area approximately 1.5-2.5km to the northwest, indicating glacial transport in this direction. The elements Sr and CaO indicate limestone and low scores plot in limestone on the southwest side of the flow set in particular and low scores area also found on the shale in the area. This suggests transport of limestone material either approximately 3km from the north, or approximately 5km if it was sourced from the nearest limestone to the southwest of the sample area. However, as Nb and TiO_2 are also low loading the low scores may reflect transport of material northwest from the mixed felsic and basic igneous lithologies to the southeast of the sample area.

In PC2 high loading of Sr and CaO explain the high scores observed on limestone in the sample area. High scores continue over shales in the north and southeast of the flow set indicating glacial transport over these areas of <1km to the north. The low loading element group Th, Ga, Rb and K_2O indicate clay minerals and low scores are found in close association with the shales and also over limestones in the west of the sample area. This shows transport of clay rich material <1km to the northwest.

3.2.4 Unknown: lineation flow set 42

LIN fs42 is found in central county Donegal and the geology of the flow set area is composed of Proterozoic psammites, pelites and quartzites with limited outcrops of limestone and metabasalt (Fig. 43). The northeast of the flow set contains the Southern Highland Group, in the centre and west are the Mullyfa, Aghyaran and Termon Formations and the south-west has the Lough Esk Psammites, Boultypatrick Grit and the Croaghubrid Pelite. General flow direction as interpreted from subglacial bedform morphology is to the northeast, though the small size of bedforms did not allow the glaciological context of the flow event to be confidently determined in the original study by Greenwood and Clark (2009a, b).

3.2.4.1 Principal component scores for samples within LIN fs42

LIN fs42 has 137 sample points on till and PCA returned seven PCs that together account for 82.3% of the variance in the data. NB only the most illustrative PCs are presented in this report. The remainder of the PCs can be found on the CD-ROM of additional material that accompanies this report.

PC1 accounts for 36.3% of the variance in the data and the highest loading elements (>0.25) are Ni, Fe_2O_3, Cr, Al_2O_3, Zn, Sc, Cu, V and Co (Fig. 44). Concentrations of high scores associated with these elements are observed in the northeast and south to central sections of the sample area (Fig. 45). The lowest loading (<0.1) elements are As, La, Hf, Sr, Se, CaO and Rb and there are no negative loading elements. Low scores are found in the central to north and southern parts of the flow set.

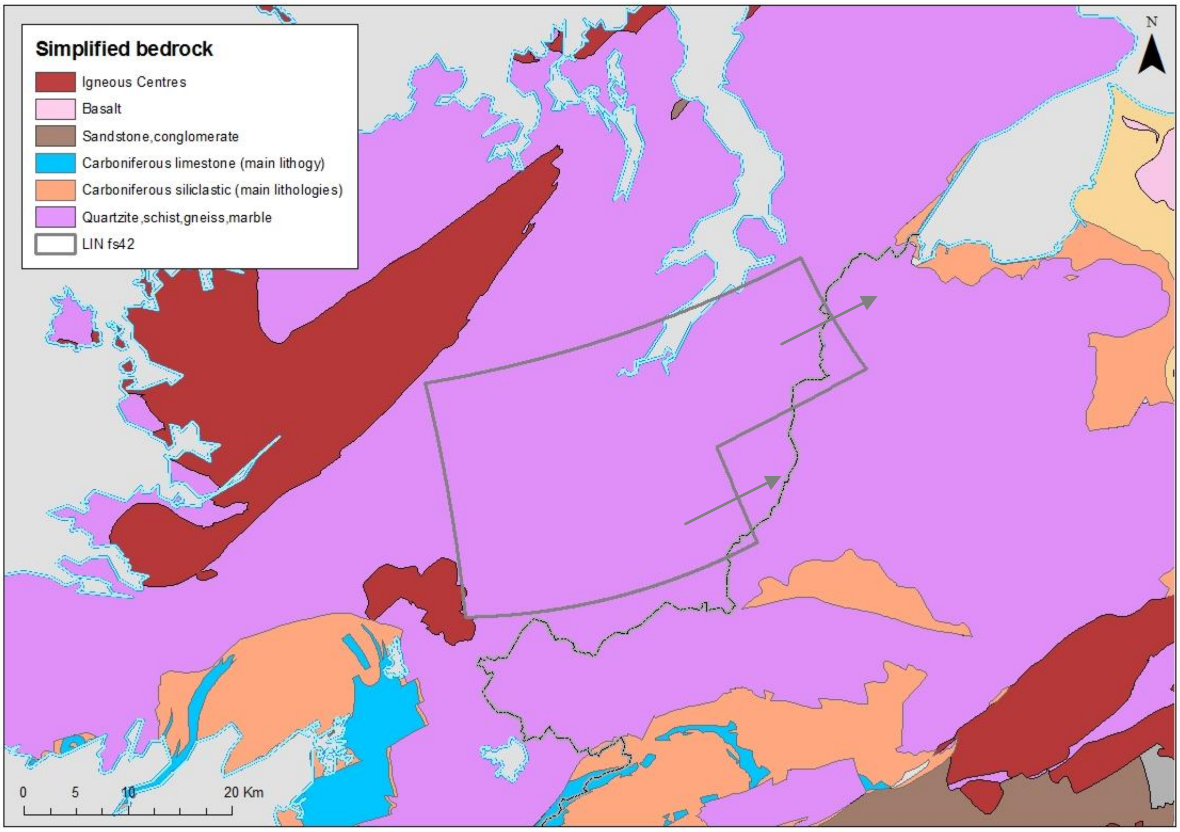

Figure 43. Simplified geology for northwest Ireland, with LIN fs42 extent.

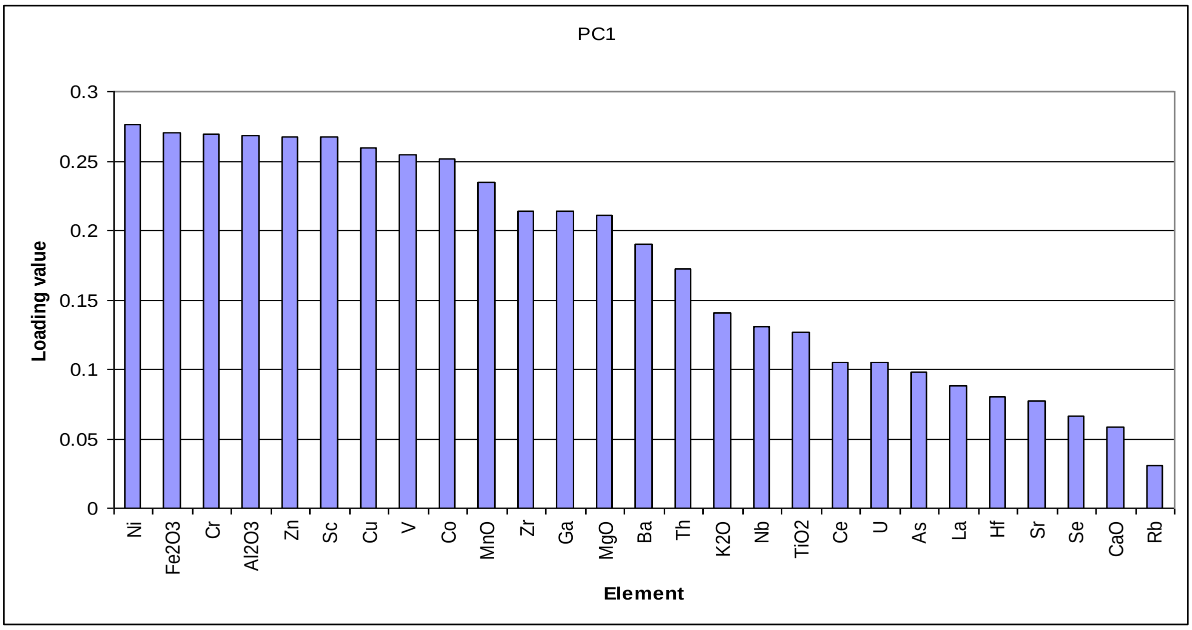

Figure 44. Element loadings for Principal Component 1, LIN fs42 sample area.

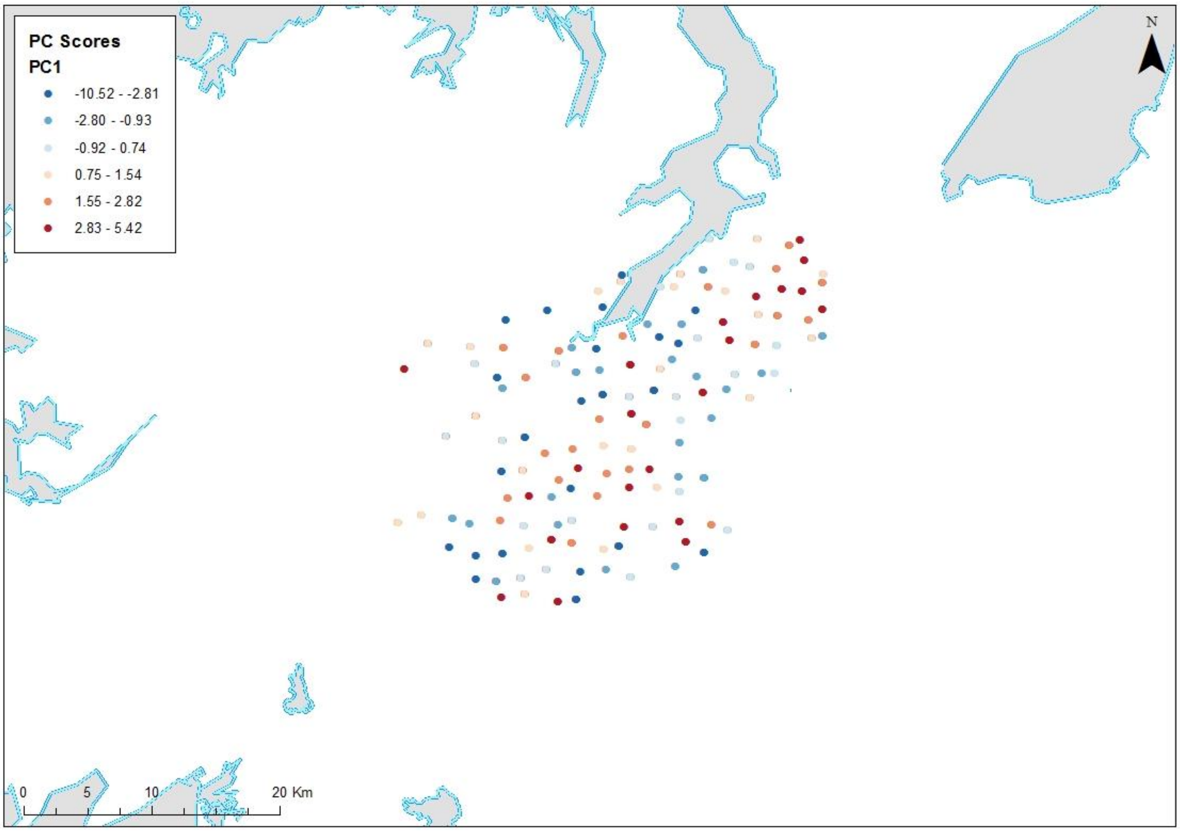

Figure 45. Principal Component 1 score distribution for LIN fs42 sample area.

PC2 (14.9% of the variance) has highest loading (>0.2) elements Ce, La, Th, U and Rb (Fig. 46) with associated high scores found over the central and southern sections of the flow set (Fig. 47). Lowest loading elements (<-0.14) are CaO, Cr, V, Nb and TiO_2 and a concentration of low scores is found in the north-east of the sample area with scattered low scores observed through the rest of flow set.

PC3 explains 9.1% of the variance and the highest loading (>0.2) elements are Sr, U, CaO, Sc, TiO_2 and Nb (Fig. 48) with two areas of high score concentrations observed in the north-east and south of the flow set (Fig. 49). Lowest loading (<-0.12) elements are MnO, Fe_2O_3, Al_2O_3, Ba and K_2O with associated low scores found in an east-west oriented band in the central to northern section of the sample area.

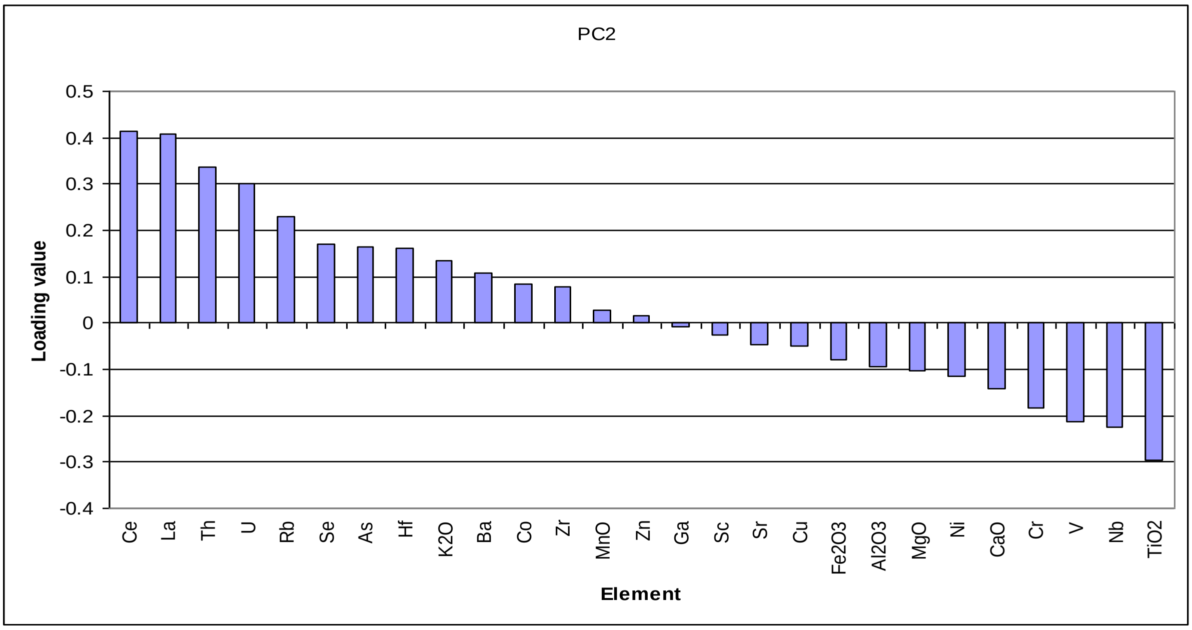

Figure 46. Element loadings for Principal Component 2, LIN fs42 sample area.

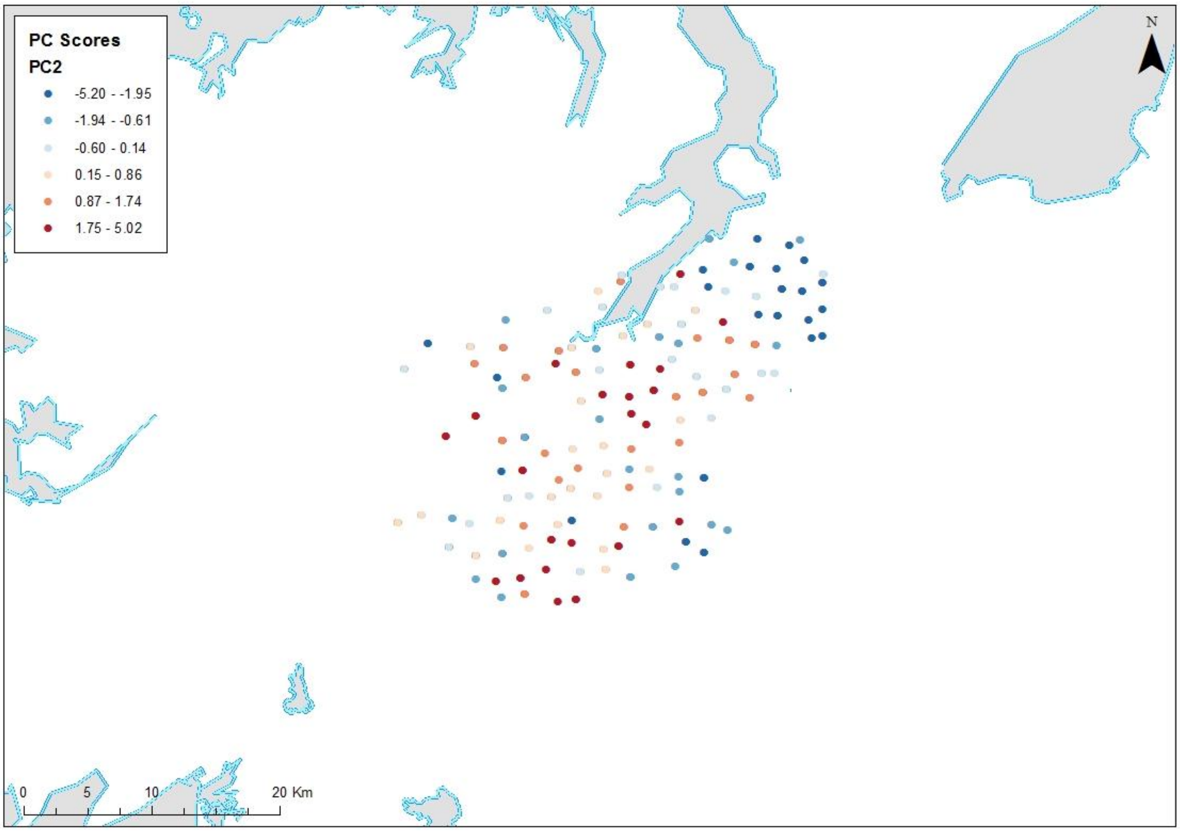

Figure 47. Principal Component 2 score distribution for LIN fs42 sample area.

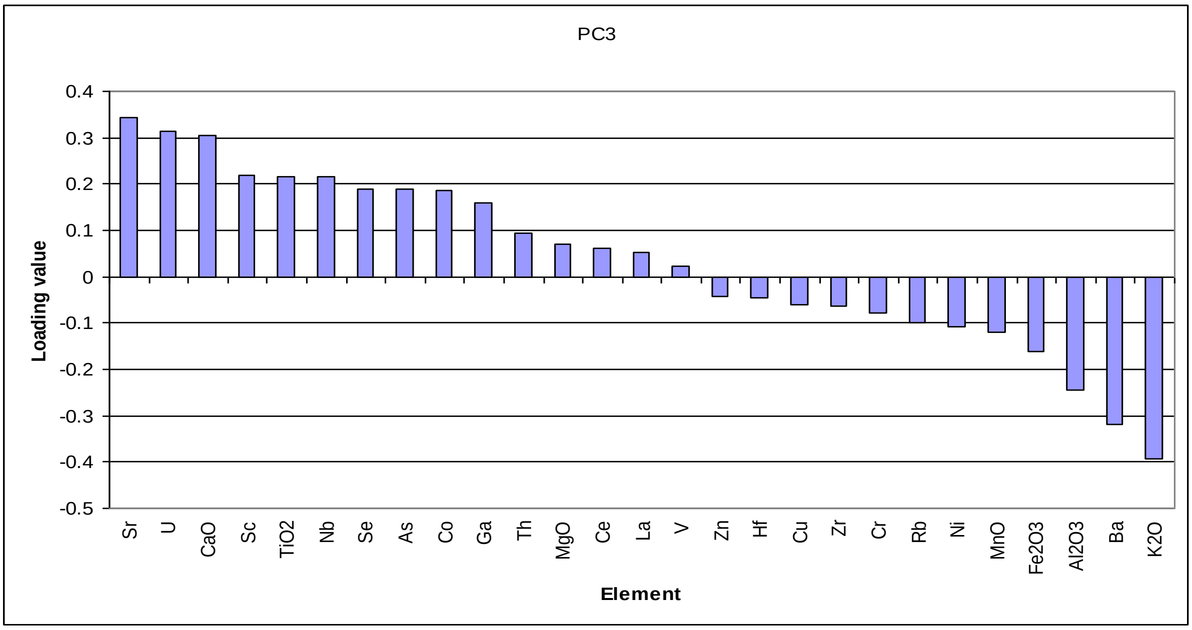

Figure 48. Element loadings for Principal Component 3, LIN fs42 sample area.

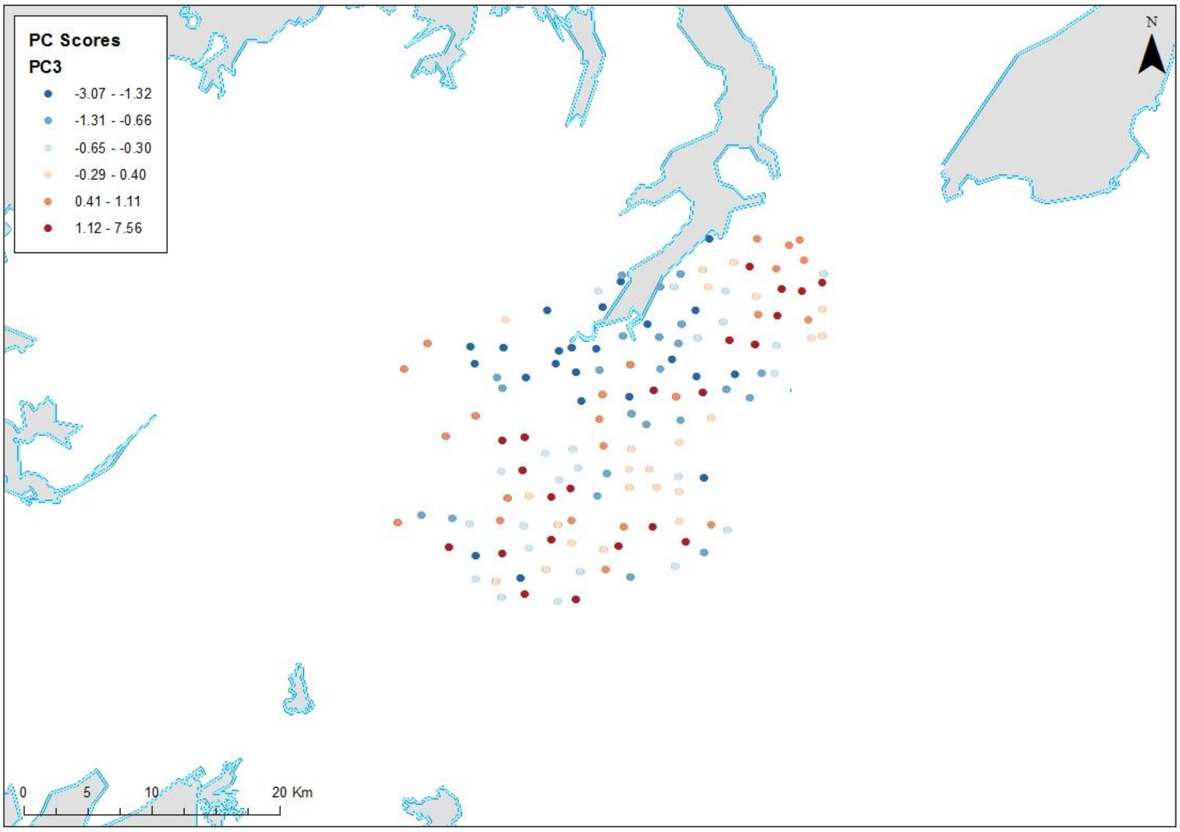

Figure 49. Principal Component 3 score distribution for LIN fs42 sample area.

3.2.4.2 Interpretation of PCA results from LIN fs42

The high loading of elements Ni, Fe_2O_3, Cr, Al_2O_3, Sc, V and Co together in PC1 indicate a clay mineralogy and high scores are found on schist in the northeast of the sample area but also on psammites and quartzites in the central part of the sample area. The central section is heavily faulted so the high loading of Zn and Cu may indicate mineralisation and contribute to the high scores here. The low loading of Sr and CaO indicate carbonates, and La, Se and Rb feldspar or clay minerals and low scores do occur in association with marble/limestone bearing units in the northeast and feldspathic psammite in the southwest.

For PC2 the high loading element group Ce, La, Th, U and Rb suggest either felsic igneous rocks or metamorphosed mud rich sediment and high scores correlate with pelites, schists and psammites in the sample area. The low loading of CaO indicates carbonates, Cr and V clay minerals and Nb with TiO_2 metamorphic minerals. Low scores are concentrated in the northeast of the sample area on the Southern Highland Group which contains mixed metamorphic sediments, so match well with the low loading element group. However, there is a very sharp transition from high to low scores in this region that does not conform to a lithological boundary, so the high scores here may represent glacial transport of material from the semi-pelites and schist of the Termon Formation approximately 8km to the northeast.

PC3 has high loading for Sr, U, CaO, Sc, TiO_2 and Nb and high scores in sample area reflect the mixed lithologies in the northeast and southwest of the sample area. The low loading element group of MnO, Fe_2O_3, Al_2O_3, Ba and K_2O are indicative of clay mineralogy and low scores appear as an east-west oriented band in the northern section of the sample area, extending from the Termon Formation (semi-pelites and schist) in the west and south across the Aghyaran & Killygordon Limestone Formation and Southern Highland Group. This suggests glacial transport of material approximately 8 km from the south or west.

4. SUMMARY AND CONCLUSION

PCA of the upper soil geochemistry of Tellus Border soil samples, used here as a proxy for till in the study area, has indicated a strong link between the till and local bedrock at the regional scale and that geochemical composition changes occur rapidly across lithological boundaries. The score distribution map for PC1 for the survey wide analysis in particular (Fig. 7) demonstrates this, with the high score distribution closely following the outcrop boundary of the greywacke and shale of the Down-Longford terrane, with low scores recorded immediately to the north-west of the bedrock boundary (see also supplementary material on accompanying CD-ROM). This close association with local bedrock is also observed in the analysis conducted on the various flow sets (Section 3.2), showing that patterns recorded in the survey wide analysis are also repeated at the flow set scale. The PCA of metals, semimetals and pathfinder elements (section 3.1.2) also exhibits this strong link to known local bedrock occurrence. Therefore, the overall conclusion of the project is that the main element associations and spatial distribution patterns derived from PCA of the Tellus Border soil geochemical data indicate that the majority of till deposits in the survey area have been locally derived. This indicates till transport distances overall in this sector of the Irish Ice Sheet were low, as different bedrock regions retain predominantly uniform PC scores. Rates of evacuation of subglacial debris to the ice margins must also have therefore been low.

By extension, this also indicates that the geochemistry of the subglacial bedforms within the study area must also reflect the local bedrock on which they are found. This has interesting implications for researchers working on formational theories that try to explain the genesis of these landforms. Since the results indicate that the tills in the study area are locally derived, then it is reasonable to argue that these landforms must be in large part be composed of locally derived materials. This idea is supported by a limited number of studies that discuss the internal composition of these landforms from within the study area and further afield. For example, Knight and McCabe (1997) describe a section in the Mullinasole drumlin in the coast of Donegal Bay, which is part of the flow set LIN fs35 (Fig. 20), and report that the internal structure contains locally derived striated limestone clasts. There have been limited observations of the internal structure of ribbed moraines, but a comprehensive literature review of published accounts of this landform indicates their internal composition often consists of locally derived materials (Hättestrand, 1997). For ribbed moraines it could be argued that low transport rates may be associated with their geographic location within an ice sheet since they tend to be found clustered (although not exclusively) around former ice divide positions (Dunlop and Clark, 2006) where ice velocities would have been low. However, it is difficult to argue that this is the case for drumlins, which are typically associated with faster ice flow (e.g. Clark, 1999) for example ice streams, where velocities are much higher than what is typically observed within the main body of the ice sheet. A number of competing theories exist for both drumlins and ribbed moraines (e.g. Dunlop et al., 2008; Hättestrand, 1997; Knight and McCabe, 1997; Clark, 2010) with no general consensus reached between researchers. The observations made in this study is an important contribution to this area of research because to be considered as a credible formational theory, it can be argued that they now need to explain how subglacial bedforms can be generated as a consequence of low sediment transport rates.

Even though the study has shown that till deposits are locally derived, transport of till across lithological boundaries can be detected at the regional scale and in the flow set analyses. Where it is observed the inferred direction of transport from the geochemistry is in agreement with the flow directions indicated by bedform geomorphology in the immediate area. For example in PC1 (Fig. 7) of the regional analysis and LIN fs9 (Fig. 32) the high scores associated with the turbidites in south county Monaghan continue south-east over Carboniferous limestone and Triassic sandstone, and this transport direction is parallel to the southeast ice flow direction indicated by published geomorphological mapping. Subglacial transport is detected in the analyses of each of the glaciological contexts (flow sets) presented, ranging from <1 km (LIN fs22, section 3.2.3) up to approximately 12 km (LIN fs35/37, section 3.2.1). Once again, the transport directions suggested by the geochemistry agree with flow directions as indicated by bedform geomorphology. No particular glaciological context appears to favour transport though the greatest inferred transport distance appears in an area with two cross cutting isochronous flow sets (LINfs35/37, section 3.2.1). In PC3 of the 'Unknown' flow set (LIN fs42, section 3.2.4) the geochemistry does contain evidence of transport to the north/east as inferred by the scant bedform geomorphology for the flow set, but the presence of potential parent material to the south and west means it cannot be fully resolved as two other flow sets (LIN fs40 and 41) that show northward ice movement are recorded in the area (Fig. 3 and supplementary material on the CD-ROM). The presence of geochemically distinct rocks adjacent to one another in all examples improves identification of the signal e.g. limestone/greywacke & shale, igneous/country rocks. It is worth noting that even though the bedrock geology of the region is diverse in terms of distinct formations and rock category, large areas are essentially compositionally similar. For example, the Proterozoic rocks in Donegal and the northwest of Northern Ireland are metamorphosed mudstones, sandstones and limestones and the adjacent Carboniferous sequences in the study area are composed of mudstones, sandstones and limestones. These rocks can be readily separated the field by their textural differences, but their bulk geochemistry will show a high degree of similarity.

Although the primary purpose of this project was to investigate glacial sediment provenance, it is worth highlighting some of the results of the metals, semimetals and pathfinder element analysis. No significant glacial dispersal was detected and metal occurrence shows a link to local bedrock, but an anomaly appears through the results in PC4 of the regional analysis and PC2 in the metals only analysis. The high scores in PC4 of the regional analysis are associated with the elements TiO_2, V, CaO, Cu, Cr and Ni (Fig. 11). Areas of limestone and Ca rich rocks show a correlation with high scores that may be explained by the high loading of CaO, but there are areas of high scores that occur on greywacke and shale in east Monaghan and south Cavan, which exhibit a distinct pattern, with two main bands oriented north-east/south-west. The western band coincides with the outcrop of the Gilnahirk Group/Red Island Formation of the Down-Longford Terrane, but the eastern band does not appear to follow a stratigraphical boundary or orientation consistent with glacial dispersal. The association of Ni, Cu and Cr in these areas may indicate potential mineralisation, and the PC2 scores for the metals only analysis (Figs. 15 and 16) also highlights these areas, correlating with the element grouping of Ni, W, Al, Cr, Ti and Nb.

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